US Army Corps
of Engineers

Topographic Engineering
Center

Final Report
CPAR-TD-96-1
August 1996

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Construction Vehicle Navigation and Automation

by

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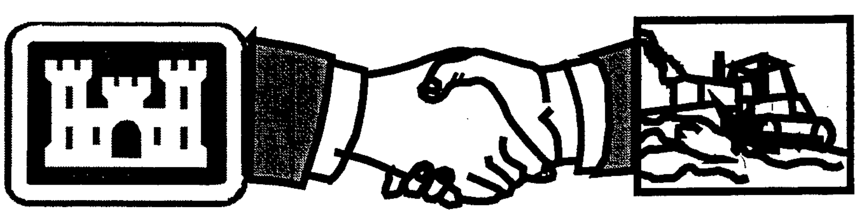

AD NUMBER	DATE	DTIC ACCESSION NOTICE

1. REPORT IDENTIFYING INFORMATION

A. ORIGINATING AGENCY
U.S. Army Topographic Engineering Center

B. REPORT TITLE AND/OR NUMBER CPAR-TD-96-1
Construction Productivity Advancement

XXXXMONIXXXXREPORTXNUMBERX
Research (CPAR) Program

D. PREPARED UNDER CONTRACT NUMBER

2. DISTRIBUTION STATEMENT

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EXECUTIVE SUMMARY

The U.S. Army Topographic Engineering Center (TEC) and Caterpillar Inc. have cooperated in the joint research and development of a system to position, track, and maneuver construction and other equipment during their normal construction activities. The two main components of this research focus on the positioning system needed for navigation and the Computer Aided Drafting and Design (CADD) interface for automation.

The positioning system is based on software developed by TEC that utilizes the Global Positioning System (GPS). It is called the On-the-Fly (OTF) Differential GPS system. Several repeatability tests were conducted to test the accuracy and precision of the OTF software. The results proved that the OTF system can provide an accuracy of 3 centimeters in a robust manner.

The positioning system software has been integrated with Caterpillar developed software tools to automate construction activities and increase productivity and safety in the project area. This software allows the construction vehicle to perform its operations and provide real time as-built drawings in the process.

This joint effort has produced an autonomous construction vehicle navigation and automation system that has been demonstrated on a Track-Type Tractor (dozer) and will be adapted to various other construction vehicle platforms, which include an off-highway truck and a motor grader. CADD tools based on the envisioned vehicle navigation system have been integrated, offering the user highly accurate and responsive production, planning and monitoring tools that were previously unavailable.

INTRODUCTION

Most construction activities require some form of earth movement, whether it be grading, clearing, cutting and/or filling. Before, during and after these construction activities, site surveys are performed to verify that the project area is consistent with the engineering design. In years past, these designs were drafted by hand and interpreted by surveyors in the field as to whether the proper quantities of soil were being excavated and/or deposited. With the improved performance of Computer Aided Design and Drafting (CADD) and other automated surveying means, users are able to accurately and efficiently design and construct in the virtual world of computers. Until now that automation stopped when moved from the office computer to the project site. In other words, earth moving equipment operators relied on experience and wooden stakes accurately placed by surveyors to communicate the proper design surface.

In April 1993, the U.S. Army Topographic Engineering Center (TEC) and Caterpillar Inc. signed a three-year Construction Productivity Advancement Research Program Cooperative Research and Development Agreement (CPAR-CRDA) to develop a Global Positioning System (GPS) based construction vehicle positioning and navigation system that could be adapted to various construction equipment platforms. The final system combined the latest GPS positioning technology with a variety of CADD tools. This combination offers the equipment user computer-generated views to display and continuously update the topography during normal construction activities. The system also produces as-built drawings of the construction site that can be electronically transferred back to the design engineer for verification.

Automation of any earth moving activity requires continuous tracking of the equipment's

position in relation to the project area. This information must also be graphically relayed to the equipment operator and to the field office for monitoring the machine's progress (see **Figure #1**). Therefore, for the CPAR-CRDA to be considered successful and result in a marketable product, the positioning system and the CADD interface must operate without failure and be economically feasible in a construction environment. The positioning system and the CADD interface are the fundamental building blocks of this CPAR.

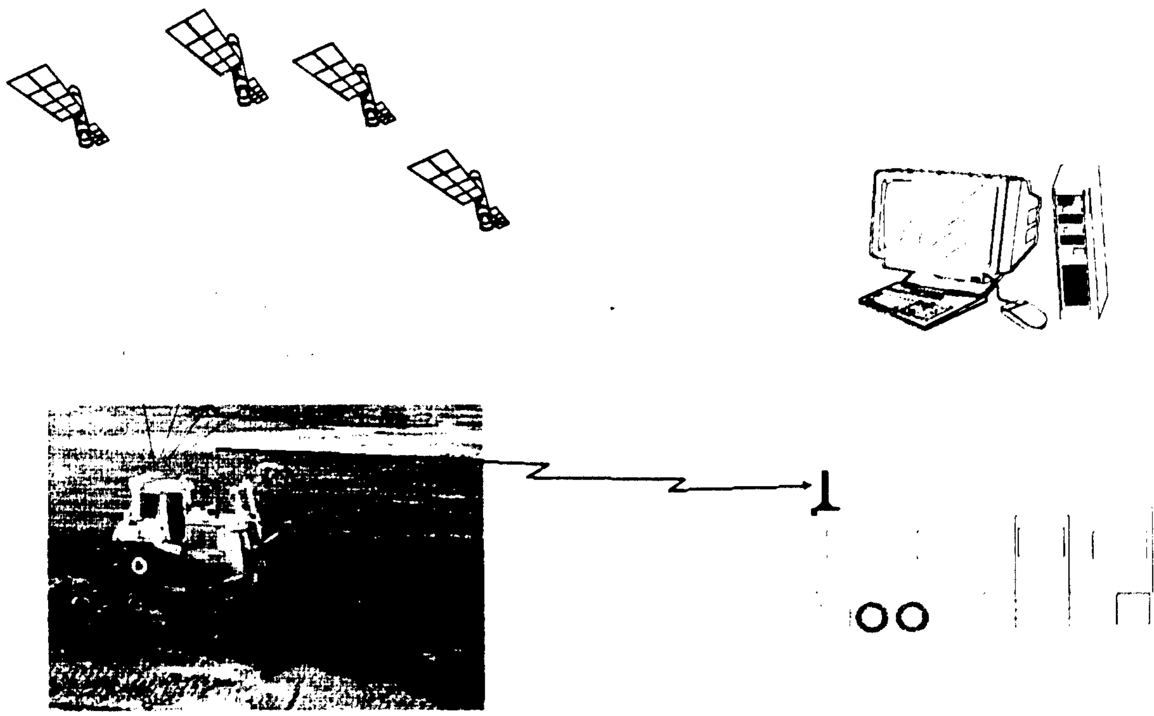


Figure 1. Schematic of Automated System

POSITIONING SYSTEM

The system developed in this CPAR project provides the equipment operator with positioning information based on GPS. NAVSTAR GPS is an all-weather, 24-hour, worldwide, three-dimensional (3-D) satellite-based positioning system developed by the Department of Defense (DoD). Each satellite broadcasts on two frequencies, L1 and L2. On each frequency coded

messages (the P-code and C/A code) are modulated or carried (see **Figure #2**). Both the carrier frequency and their coded messages are used to obtain positioning information.

Carrier	Codes		
	Civilian	Military	
L Band	C/A Code	P Code	Satellite Message
L1 (1575.42 MHz) 19 cm wavelength	Present 300 m wavelength	Present 30 m wavelength	Chipping Rate is 50 bps
L2 (1227.60 MHz) 24 cm wavelength	Not Present	Present 30 m wavelength	

Figure 2. GPS Signal Structure

The primary purpose of GPS is to provide a Precise Positioning Service (PPS) to the U.S. military and its allies. GPS also provides the Standard Positioning Service (SPS), a service available to civilians with the purchase of necessary equipment. These services are affected by the transmission from the satellites of time-coded signals unique to each satellite and information on satellite timing and positions. By measuring the arrival time of these coded signals, the GPS receiver estimates the range to each of the GPS satellites in view and then, using the satellite positions, is able to compute its own position and clock offset. When using one GPS receiver, the 3-D absolute accuracy is approximately 16 meters for PPS and 100 meters for SPS.

Differential GPS (DGPS) techniques process signals from two GPS receivers operating simultaneously and determines the 3-D vector between them. This technique can be used with the code phase information transmitted by the GPS satellites to obtain meter accuracy or the carrier information to obtain an accuracy to a few millimeters (see **Figure #3**).

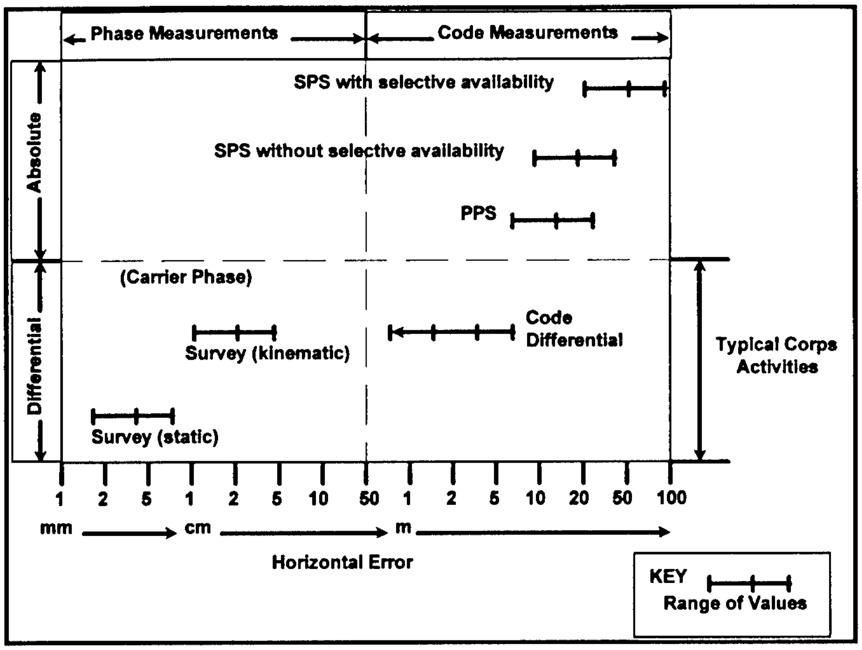


Figure 3. GPS Accuracy

In the past, a significant restriction to using GPS technology has been the ability to position accurately in real time. Until recently, the ability to position a moving platform with DGPS (to a few centimeters) required very strict operational constraints and procedures that were not feasible in a construction environment. In 1988, under funding from the U.S. Army Corps of Engineers (USACE) Dredging Research Program (DRP), TEC began developing a real time GPS-based positioning system capable of delivering 3-D positions accurate to a few centimeters over a range of approximately 20 kilometers. To obtain "centimeter" level positions in real time, the integer ambiguities (whole number of integer wavelengths) between the receiver and the observed satellites must be solved while one receiver is in motion (termed On-The-Fly (OTF)) and another is located over a known control point (see **Figure #4**). For every common epoch (one measurement of GPS carrier phase data) measured by the receivers, a 3-D vector is calculated between them establishing the position of the moving receiver relative to the reference receiver.

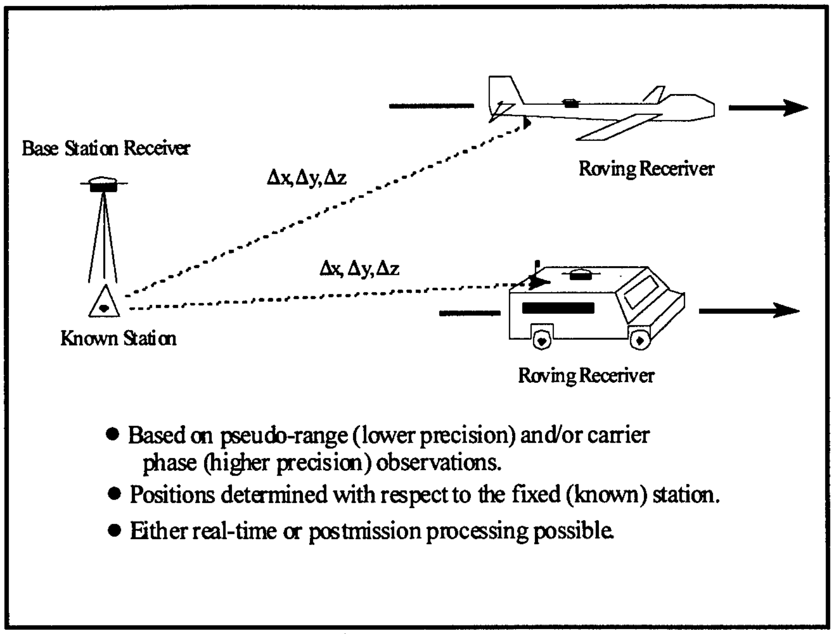


Figure 4. OTF Survey Techniques.

The OTF real-time system requires dual frequency (L1/L2) geodetic GPS receivers capable of receiving full wavelength carrier phase measurements during Anti-Spoofing (AS). AS is the encryption of the P-Code on the GPS signal. A base/reference receiver is placed over a known control monument. The raw carrier phase measurements are formatted using a computer and broadcast over a telemetry link to the roving unit or moving platform (see **Figure #5**). The rover setup requires a telemetry link (to receive reference station measurements), a computer, and a GPS receiver (see **Figure #6**). The raw carrier phase measurements from both the reference and rover receivers combined with the OTF algorithms are used to compute the rover's position in real time.

The high-precision positioning is available from the OTF system once integer ambiguities are resolved by the software. Before initialization can occur both the user and reference station must be tracking five common satellites in which the L1 and L2 carrier signals are being measured.

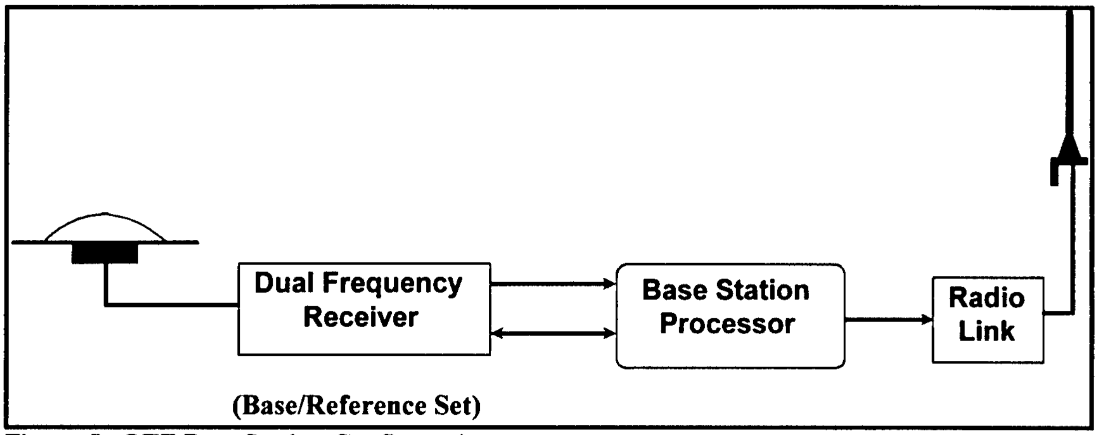


Figure 5. OTF Base Station Configuration

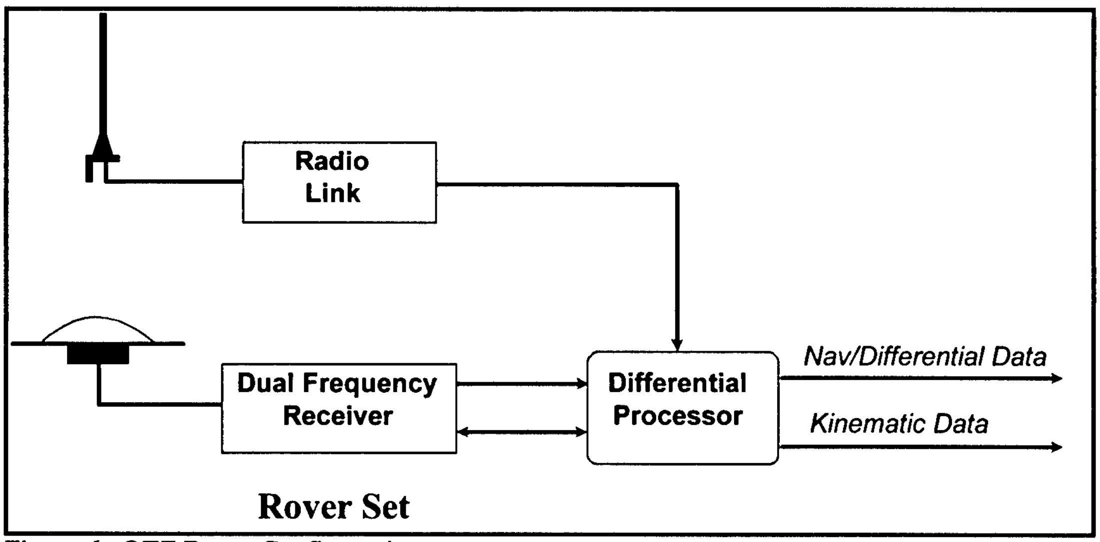


Figure 6. OTF Rover Configuration

As long as both the reference and rover receivers remain locked on at least four common satellites, real-time "centimeter" level positioning in three dimensions will continue to be available at the rover.

Under this CPAR, the OTF system was extensively tested and modified to work with Leica SR399 GPS receivers. Many tests of the OTF system have occurred since August 1993. The results of these tests have shown that the OTF system can provide a horizontal and vertical accuracy of approximately 3 centimeters in a robust manner. The OTF system offers a very

powerful tool to position accurately in real-time which results in reduced costs of construction and earth moving projects for the USACE and the private sector.

CADD INTERFACE

Caterpillar Site Data Processor (SDP)

Caterpillar has developed and demonstrated in-house, an on-the-machine dynamic construction site data base. During tests in a simulated environment, a dozer operator was able to cut a highway out of a hillside while observing an on-the-machine display of the changing work site. The SDP accepts site data design information from third-party site design tools, e.g. Intergraph CADD, AutoCad, LandCAD, AGTEK Edge, PAYDIRT, etc. and translates the design file into a data file compatible with the machine system. The site data file is transferred to the machine by either a PCMCIA flash drive or a direct radio link.

FIELD TESTING

Several experiments tested the effectiveness and feasibility of the positioning system and CADD interface. Practical tests were performed to test the integrated GPS/CADD system under typical construction conditions. Repeatability tests were also performed to test the validity of the OTF positioning system with different types of GPS receivers.

Practical Tests

Test #1. The first practical test was performed in December 1993 at Caterpillar's Peoria Proving Grounds in Peoria, Illinois. The objective of this test was to combine TEC's positioning software with Caterpillar's Dynamic Site Data Base and test its functionality on board a Track-

Type Tractor (dozer). A second objective was to determine the best possible location on the dozer to mount the GPS antenna, on the cab or on the blade.

The equipment used for this test included two Trimble 4000SSE GPS Receivers with dual frequency geodetic antennas, three notebook computers, two Trimble TrimTalk radios with antennas and a fixed height two-meter range pole. The base station GPS antenna was mounted on the two-meter range pole and set-up on a hill overlooking the project site (see **Figure #7**). The other GPS antenna was first mounted on top of the dozer cab (see **Figure #8a**) and later during the testing it was moved and mounted on the dozer blade (see **Figure #8b**).

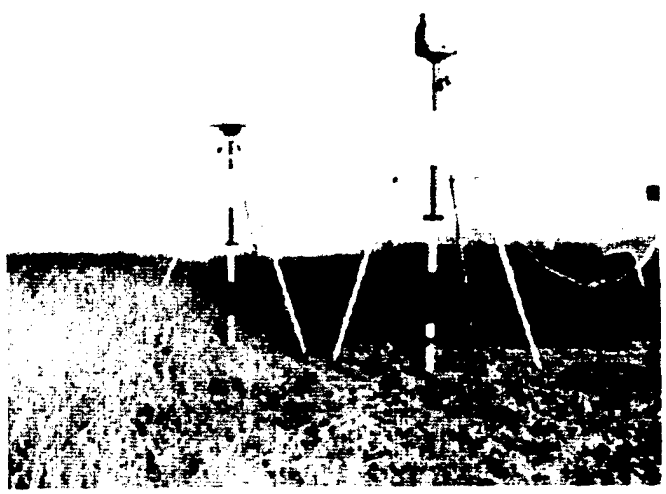


Figure 7. GPS Base Station

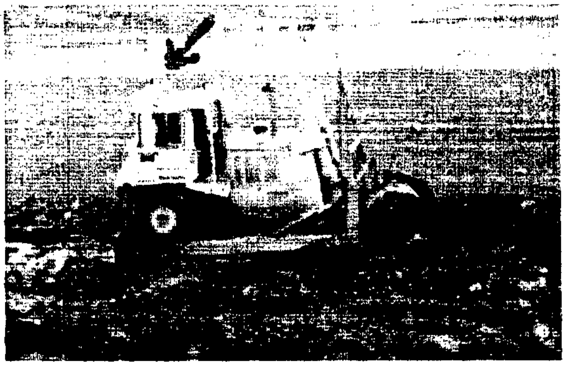


Figure 8a. GPS Mounted on Cab

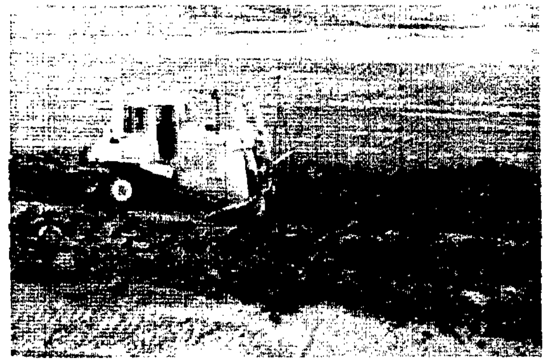


Figure 8b. GPS Mounted on blade

The machine (dozer) operator prepared a section of a highway construction site without grade stakes or a survey crew, relying on the geographical display on the machine only. Simultaneously, the dynamic construction site data was broadcast via a radio link to a remote location (in this case a notebook computer at the project site) to provide a current topographic model of the site. This experiment proved successful, because the interface between the two software packages and the operator performed without failure. The cab appeared to be the optimal location for the antenna, until a process can be developed to prevent modification of the as-built (terrain model) caused by raising the blade and moving to different sites.

Test #2. The second practical test of the joint system was to evaluate the static and dynamic performance of the positioning hardware and software with the CADD interface. Acquisition, reacquisition and repeatability were evaluated under simulated "deep open pit mining" conditions where satellites were intermittently shaded.

A reference antenna was mounted on the roof of the maintenance shop at Caterpillar's Peoria Proving Grounds. Signal splitters were used to route the satellite signals to several GPS

receivers simultaneously, and each system broadcasted their reference data independently to a corresponding receiver on the mobile rover (Machine).

The machine, a Caterpillar Belted Agricultural, was similarly equipped. A single GPS antenna and signal splitters provided the satellite signal to the various GPS receivers mounted on the Tractor. Each GPS system received its reference information separately, and independently computed a position.

The Tractor operated for a period of two weeks in various conditions, including areas with few obstructions and low multipath environment, as well as areas with partial to total satellite blockage with high multipath environment. The most challenging environment for the receivers was generated when the Tractor was driven through a metal shed which provided total satellite blockage and a high multipath environment before and after the transition.

The position computations of the various receivers agreed within the constraints imposed on the solution when each receiver system had resolved its ambiguities. The reacquisition and ambiguity resolution times varied from system to system, and needs to be shortened for acceptability in the commercial arena. However, the amount of time when high accuracy kinematic solutions are available, and can be used in the performance of a precision task, was lower than expected.

These tests provided comparative data on the repeatability of solutions, comparison of the various commercial algorithms used in the position computation, and the reacquisition and

ambiguity resolution times required leading to a kinematic solution.

The commercial technology of rubber tracks was adapted in the military arena in the form of the DEUCE (Deployable Universal Combat Earthmover) by the US Army Tank-automotive Command (TACOM). This high-speed, rubber tracked bulldozer can be made more effective by equipping it with the performance enhancing functions of the Computer Aided Earthmoving System (CAES), and the positioning and navigation system based on the GPS and a commercial form of the TEC developed OTF software.

Repeatability Tests

Three repeatability tests were performed at Caterpillar Inc. Technical Center, Peoria, Illinois. These tests were performed in December 1993, March 1994 and March 1996. The objective of this testing was to determine the repeatability of the OTF positioning software over known baselines using different manufacture's GPS receivers. These tests were conducted on a known test course (see **Figure #9**) with each point repeatedly observed during different GPS satellite constellations. During each of the three tests the OTF system was operated within 2 kilometers of the reference station providing positions at one second intervals. The initialization time was set to attempt a solution after 15 epochs had been recorded of L1 and L2 data for 5 satellites.

The equipment for the first test consisted of two Trimble 4000SSE GPS receivers with geodetic and kinematic antennas, two notebook computers, two Trimble TiimTalk radio/modems, a 2-meter fixed height tripod and a bipod. The base station was set-up on Point 5 of the test course using the 2m fixed height tripod. The position of this point had been established by a local

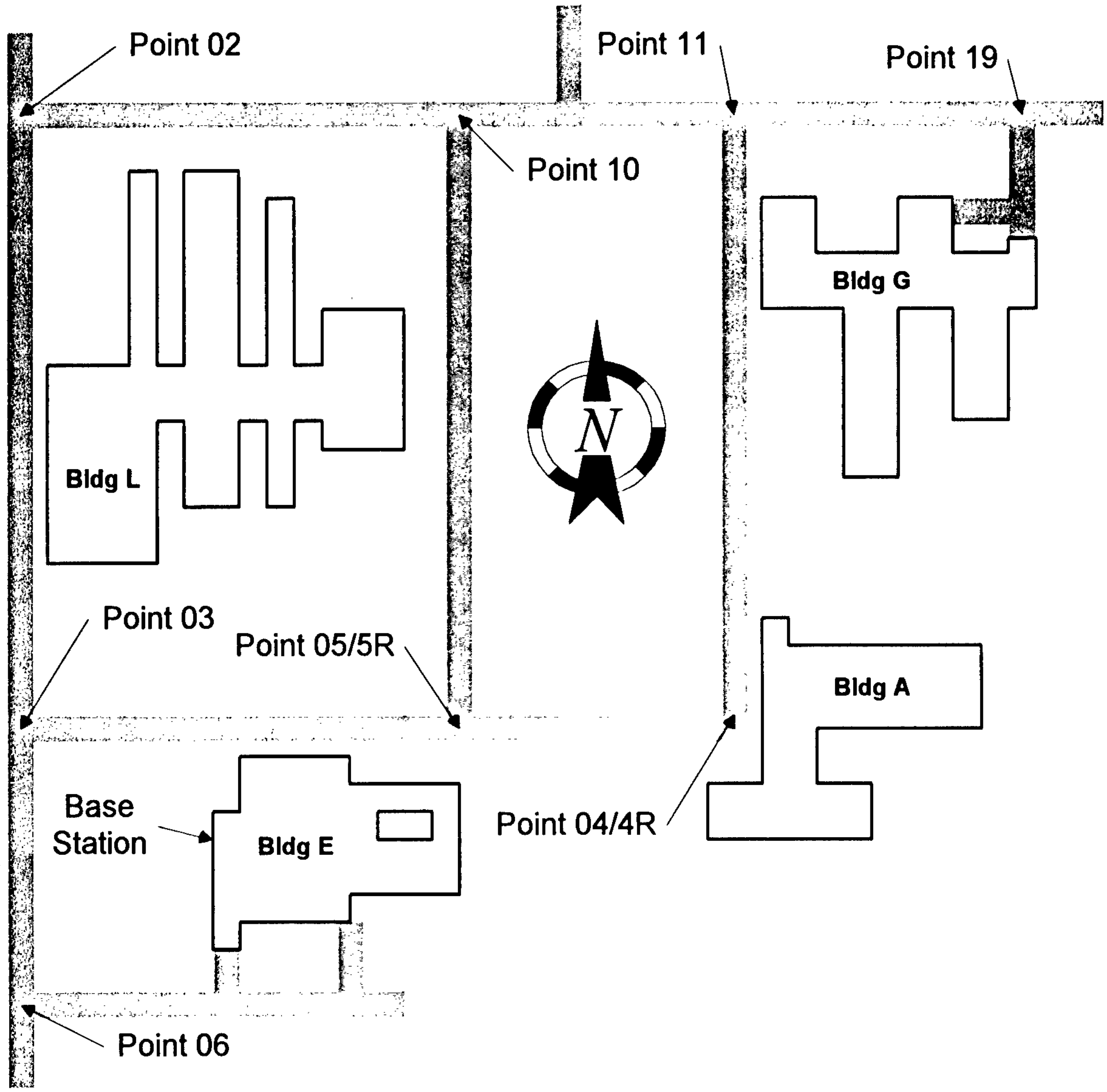


Figure 9. Caterpillar Technical Center

surveyor using traditional surveying procedures (non-GPS). The roving antenna was mounted on the bipod which attached to a roof mount of TEC's Chevy Suburban (**Figure #10**). During this initial repeatability test, observations were made on a few of the established marks around the test course. Although the results from the OTF solution were consistently within one decimeter, the test was marred by constant radio/modem and GPS signal loss at several points. The radio and GPS signal loss was due to shading as the vehicle passed close to high buildings

where satellite obstruction angles as high as 68 degrees were not uncommon. In an open pit mining operation, the high walls could reach 60 degree mask angles and are to be accommodated in the system development. Therefore, a fast reacquisition and ambiguity resolution is mandatory for commercial mining and construction applications. A follow-up repeatability test was scheduled for March 1994.

Figure 10. Repeatability Testing

The equipment, reference station and procedures used for the second test was identical to the equipment which was used for the first. However, there were only a few radio/modem losses observed which did not impact the test. To demonstrate the repeatability of the OTF solution, two testing sessions were scheduled. The first session was conducted on 14 March 1994 between 19:52 and 21:47 (UTC) observing seven stations around the test course. For each station, the known position was computed by averaging the OTF solutions obtained during the first occupation. This averaged position served as the baseline for comparison of all subsequent

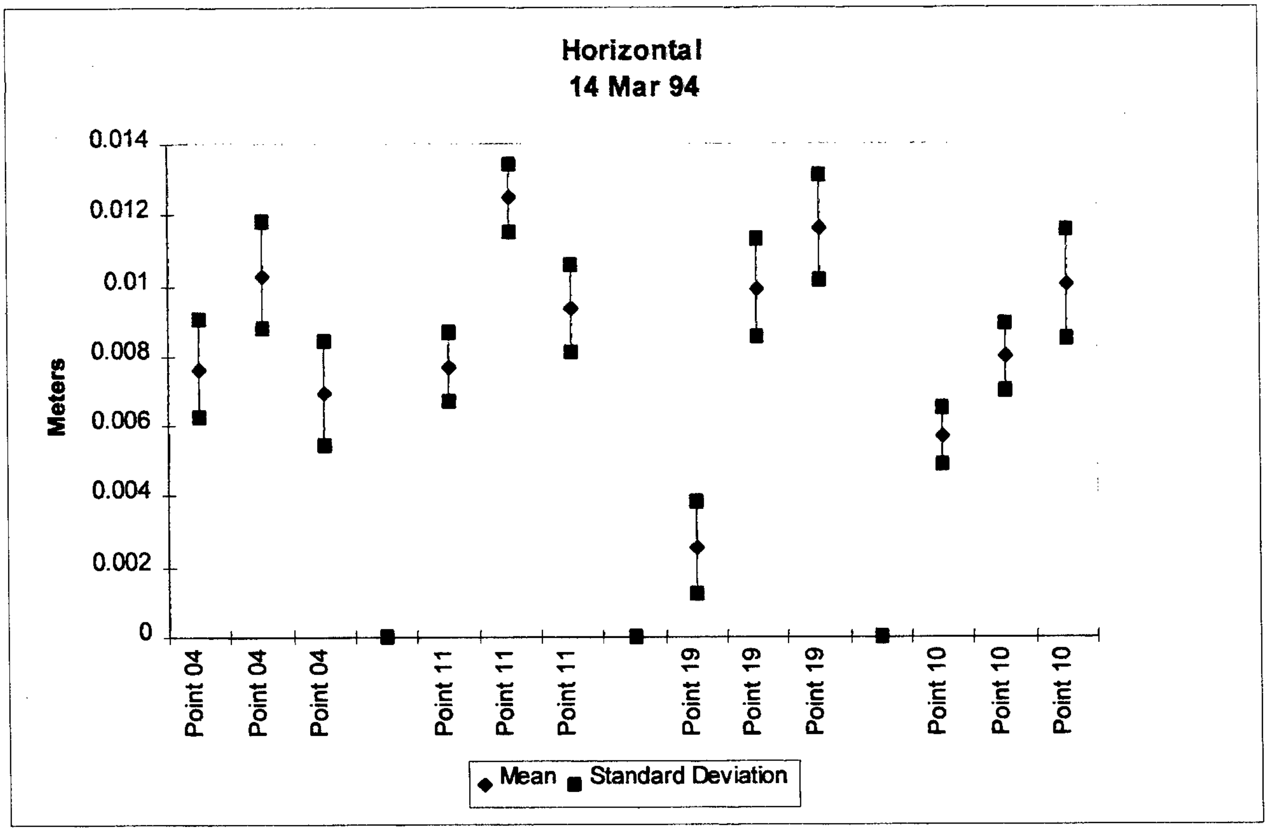
observations in both sessions. Horizontal and vertical results for each station occupation are shown in **Appendix A.** The second session was conducted on 15 March 1994 between 14:19 and 17:01 (UTC) observing three stations which were observed the previous day. The horizontal and vertical results for each station occupation are shown in **Appendix B**.

The equipment used for the third test consisted of two Leica SR399 GPS receivers, two notebook computers and a two-meter fixed height tripod. The base station was set-up on the roof of Building E of the Technical Center. The roving GPS antenna was mounted with a quick release on a two-meter fixed height tripod and transported from point to point via a Caterpillar construction van. This test was conducted on 28 March 1996 between 19:17 and 21:37 (UTC) observing eight stations around the test course. The known positions of the reference and test course stations were established by GPS static surveying procedures. Horizontal and vertical differences between the OTF solutions and the known positions for each station occupation are shown in **Appendix C**.

ANALYSIS OF RESULTS

Repeatability Test

The performance of the OTF system yielded a positional (horizontal and vertical) difference of 0.0183 m ± 0.0101 (95% confidence interval). These repeatability tests demonstrate the positional accuracy and precision of the OTF system. The following graphs show the individual horizontal and vertical averages and standard deviations of each occupation separated by test.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Meters
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0.012
0.01
0.008
0.006
0.004
0.002
0
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Point 04
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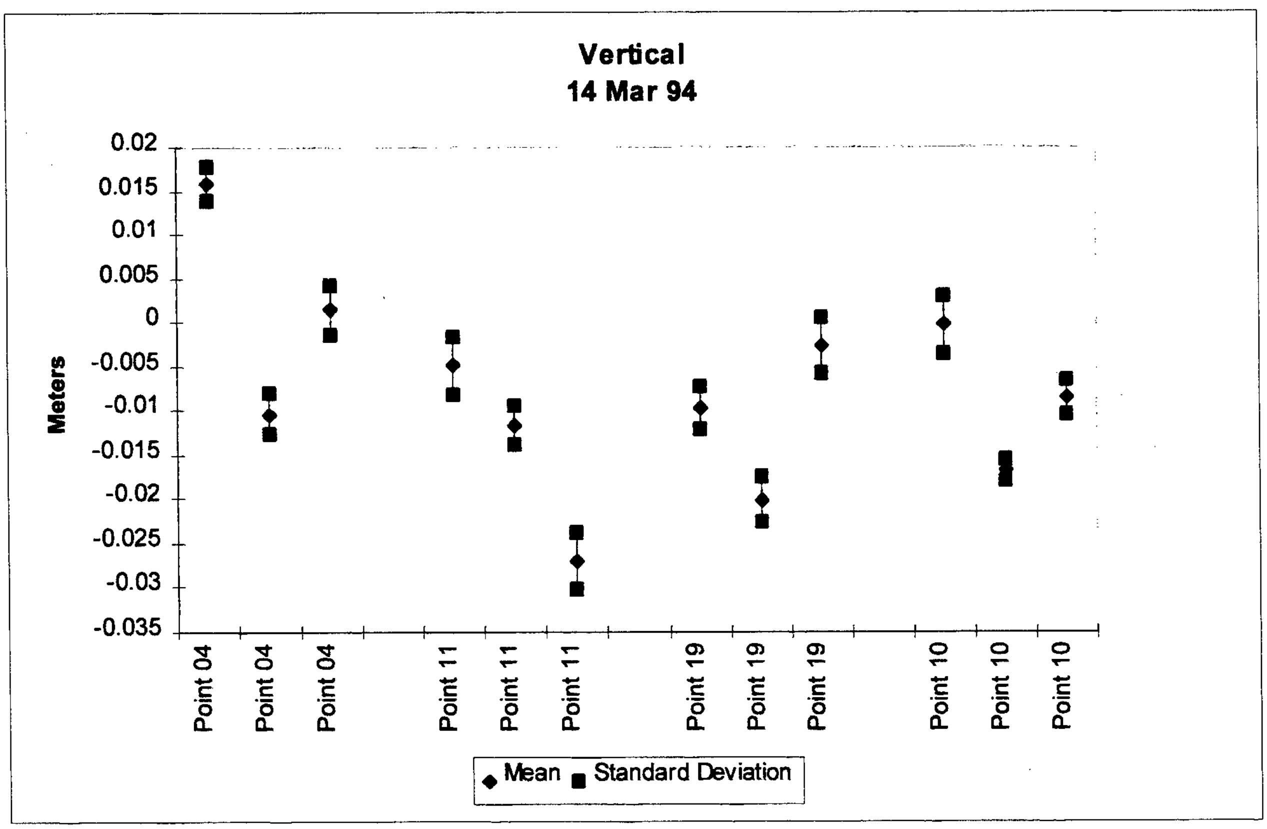
Point 11
Point 11
Point 19
Point 19
Point 19
Point 10
Point 10
Point 10
Mean
Standard Deviation


Vertical
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Meters
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0.01
0.005
0
-0.005
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-0.015
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-0.03
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Point 04
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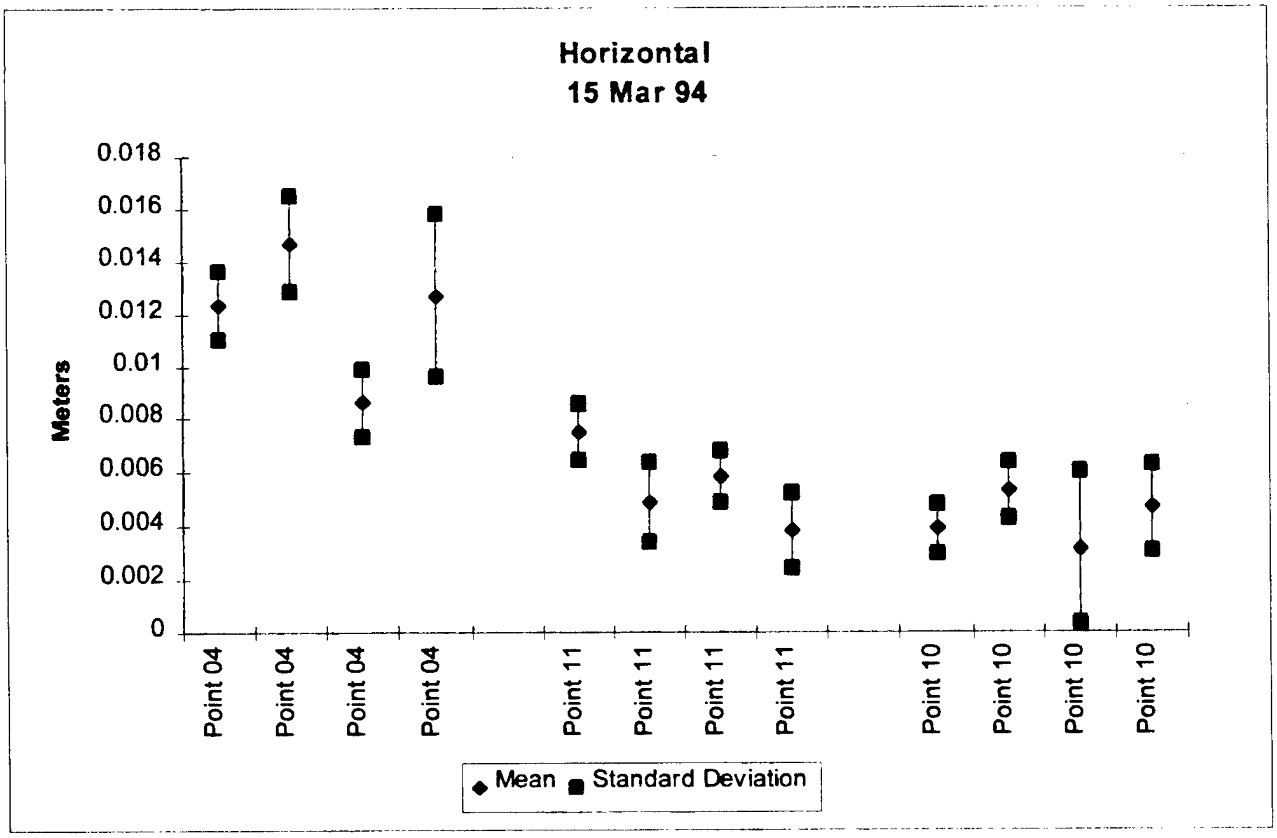
Point 11
Point 19
Point 19
Point 19
Point 10
Point 10
Point 10
Mean
Standard Deviation



Horizontal
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Meters
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0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
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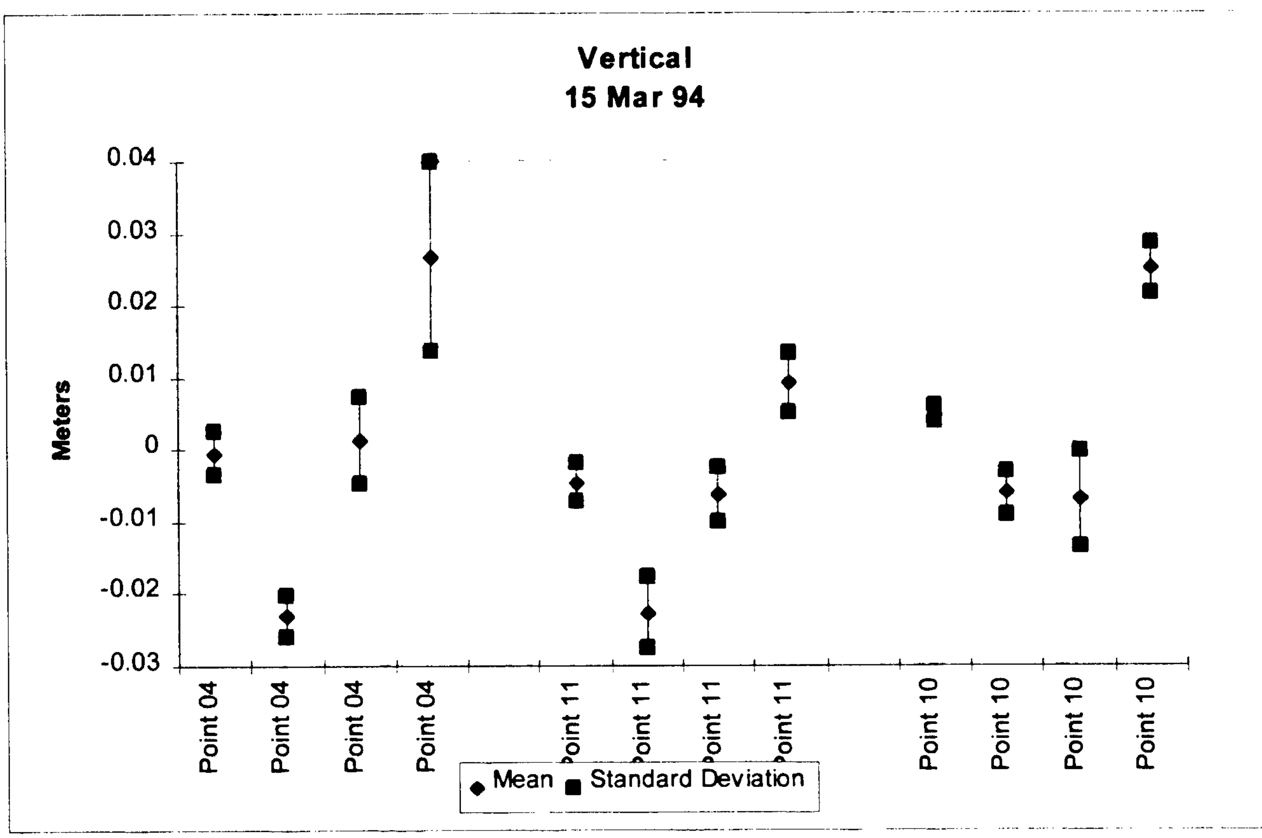
Mean
Standard Deviation



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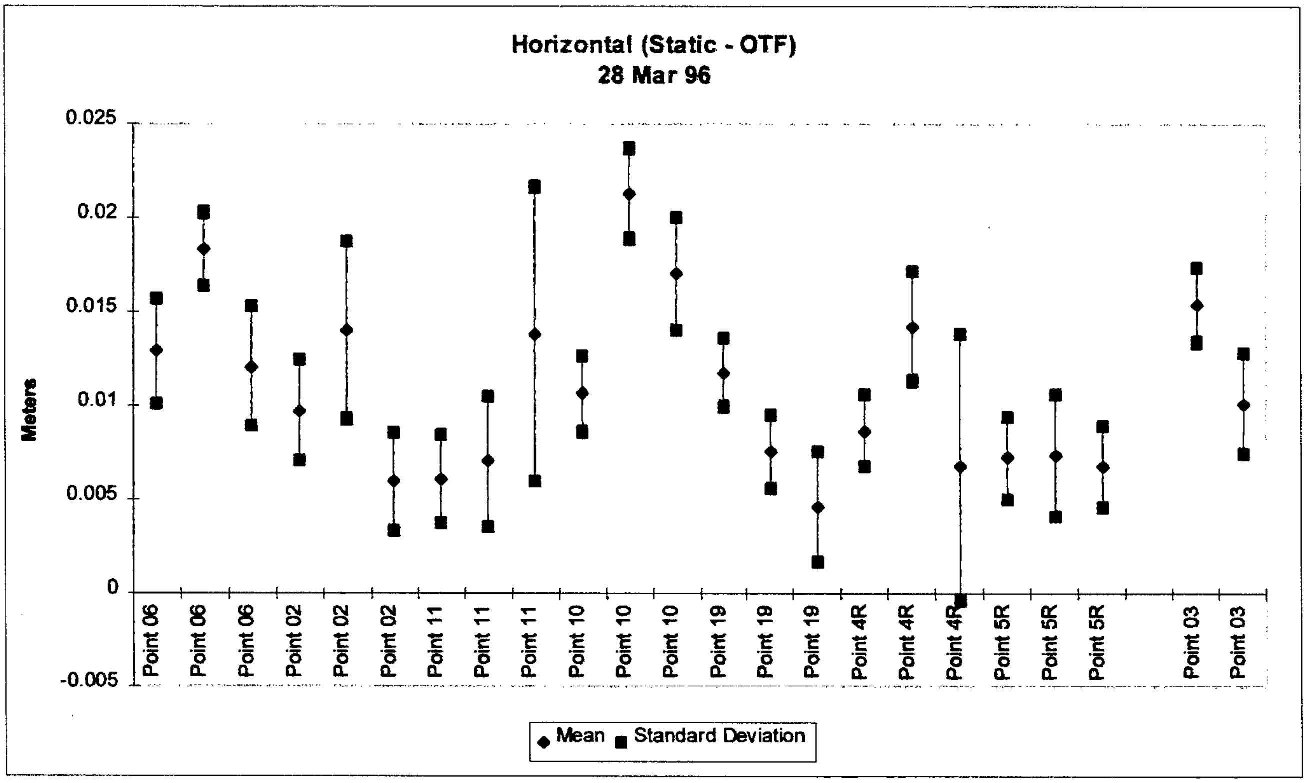
Mean
Standard Deviation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Point 11
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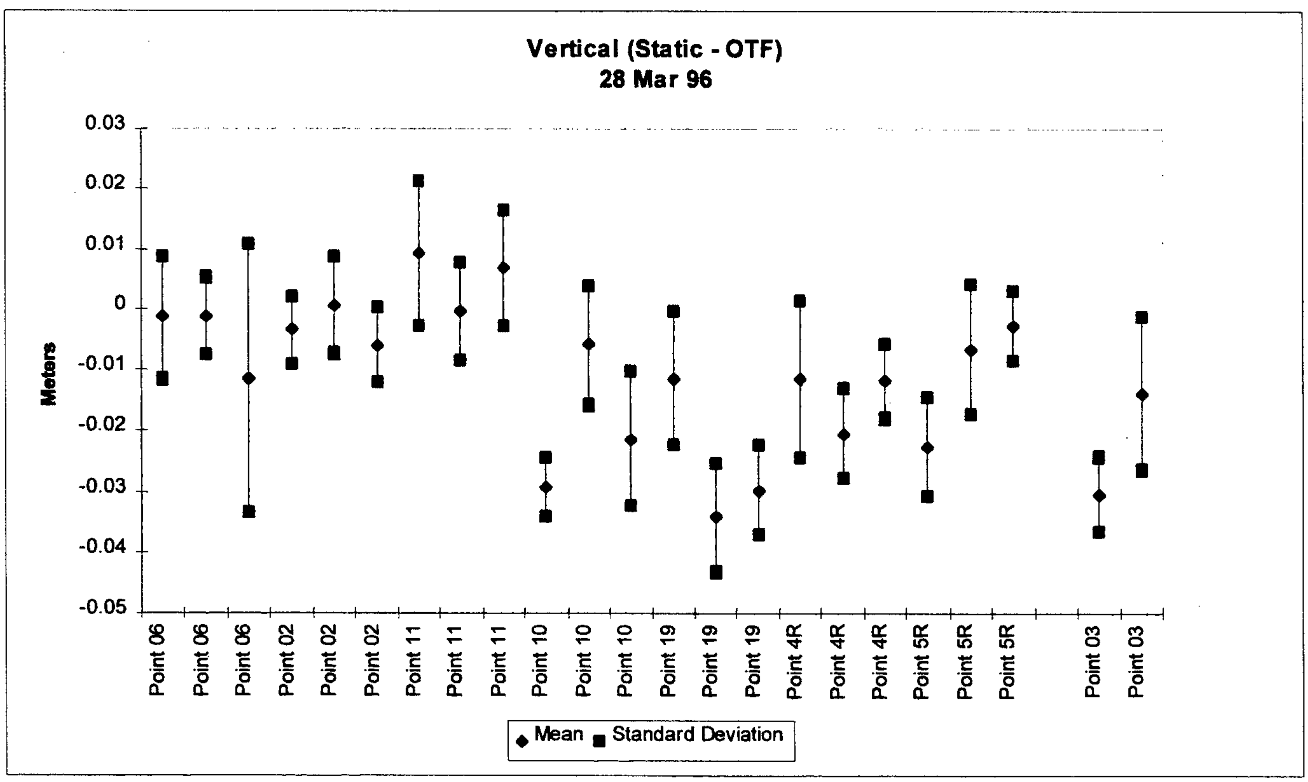
Point 4R
Point 5R
Point 03
Mean
Standard Deviation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Meters
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0.01
0
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Point 06
Point 02
Point 11
Point 10
Point 19
Point 4R
Point 5R
Point 03
Mean
Standard Deviation

DEMONSTRATIONS

Caterpillar participated in the US Army Corps of Engineers Senior Engineer Leadership Training Conference (SELTC) held at Fort Leonard Wood, Missouri (24-28 April 1995). TEC provided Caterpillar with Intergraph CADD design drawings for a fuel bladder. This design was combined with a topography of the demo area and transferred to the CAES which was installed on a D-7H Dozer and 815 Compactor. The two machines performed separate tasks using CAES.

The D-7H Dozer partially constructed a level pad and a protective berm for a fuel blivet in support of aircraft refueling operations. The machine operator relied on the CAES display screen to construct the fuel berm without any previously placed survey stakes or any support crew on hand. The display showed the operator a depiction of the current topology, the desired finished topology, the machine location on the site, and the cut-and-fill needed to complete the task. The machine operator's display monitor received a continuous update of the topology display in real-time as the machine made the topology altering cut. This system increased his efficiency and reduced the manpower requirements on the site. Simultaneously, the audience viewed the operator's display as the task progressed. The machine data was transmitted by radio to a remote "Command/Control" center and displayed on a large screen in front of the audience.

The Cat 815, High Speed Compactor, was also equipped with a CAES. In this case, the CAES is used to track the progress of the Compactor in performing the required number of passes over the construction site. The site was divided into a grid. The system kept track of the number of passes over each grid element. The color scheme changed until the desired number of passes had been reached. Again, the machine data was transmitted by radio and displayed on the large

screen in front of the audience showing them the machine's track and path.

Both the positioning system and the CADD system on board the machines operated without failure during the demonstration. This test demonstrated the value of an OTF-CADD automated system to the construction industry.

CONCLUSIONS AND RECOMMENDATIONS

Based on the test results from the OTF positioning system combined with the CAES, an on-machine dynamic data base coupled with GPS provides the machine operator instantaneous feedback of his performance and provides management timely progress information during site development. In addition, site design information can be reliably transmitted to the machine and presented to the machine operator on a daylight readable color screen. Also, The position of the machine tool can continuously be measured and compared to the spatial coordinates of the site to generate and maintain as-built site data files. The machine, using geodetic quality GPS equipment, continuously performs the surveying operation while simultaneously shaping the site to conform with the planned design.

The results achieved under this CPAR-CRDA support the continued development of the OTF positioning software utilizing commercial suppliers of GPS hardware to provide enhancements for evolving commercial and military products. The further development of the CAES technology will allow the smooth transition from the current terrain to the site design. This scenario creates an optimal relationship between the machine operator, the work site and technology.

DESCRIPTION OF FINAL PRODUCT

The hardware of the on-board information system consists of a GPS receiver, a computer processor, a daylight visible display with an operator interface and a set of data radios.

Computer Aided Earthmoving System (CAES)

The Caterpillar CAES uses high-accuracy GPS receivers in conjunction with computers and displays mounted on earthmoving equipment to provide machine operators and site managers with a variety of real-time information regarding the execution of the earthmoving task. On-board information systems provide the machine operator the information he needs to correctly and accurately accomplish the earthmoving task. Generally, the information includes the engineering plan, the current status of the job, the machine location, the job site, and specific information for controlling the machine's working tool, i.e., the blade, bucket, etc. As the machine accomplishes the tasks, the on-board information system records that accomplishment for later transmission to site management and engineering facilities. (See **Appendix D** for a complete description).

PLANS FOR COMMERCIALIZATION

Based on the CAES demo at USACE SELTC in April 1995 and further discussions, the Army Engineers at Ft. Leonard Wood have defined two applications in addition to the normal construction operations that they believe could be of great value to them. They are: improving operator efficiency with less training requirements and blade control for mine clearing operations.

Unlike Engineering and Management applications, on-board information systems are essentially non-existent today. They are only being made feasible by the recent advances in GPS. The accuracy and speed of GPS positioning has advanced to a stage where the position of the earthmoving machine can be accurately determined, and at a rate to provide useful information to the machine operator.

Because the on-board information systems utilize the existing infrastructure of the Engineering and Management tools, the on-machine CAES applications will be the fastest growing market. A customer may only have one or two Site Engineering and Management systems, but will have a multitude of earthmoving machines. The application of the on-board system is not limited to only the new machines, but has the potential to add value to every earthmoving machine at construction and mining sites today.

As a result of this CRDA outcome and Caterpillar's internally funded development of the dynamic data base, Caterpillar Inc. is now offering a product that combines commercial GPS receivers and positioning software in an integrated on-machine system. This product line was announced at the 1996 MINE EXPO show in Las Vegas, Nevada, and applies to Dozers, Motor Graders, Compactors, Wheel Loaders and Front Shovels.

BENEFITS TO THE U.S. CONSTRUCTION INDUSTRY

Today, most of the engineering design work is being done in a CADD environment. However, some benefits of CADD design work are lost when drawings are plotted and taken to the field as 2-D sheets. Extending this electronic automation (CADD) to the field allows the equipment operator to view and update the design/terrain information during normal construction activities. This automation eliminates the need for grade stakes on the construction site. Combining OTF positioning and CADD demonstrates the viability of bringing this construction navigation and positioning system to a truly production level system. CAES improves the quantity, quality and frequency of the information that flows to and from the office and field. This information is available , upon demand, from either the field or the office.

Relative to the currently used methods of surveying, designing, transporting paper plans, staking and extensive field supervision, CAES reduces the required manpower, reduces mistakes, minimizes material handling, minimizes machine idle time, improves the documentation and improves the job quality.

Individually and in combination the on-board information system reduces the cost of earthmoving and the associated cost of construction. This system will give Caterpillar Inc. and the entire U.S. construction industry, a considerable competitive and technical advantage in the U.S. and international construction markets.

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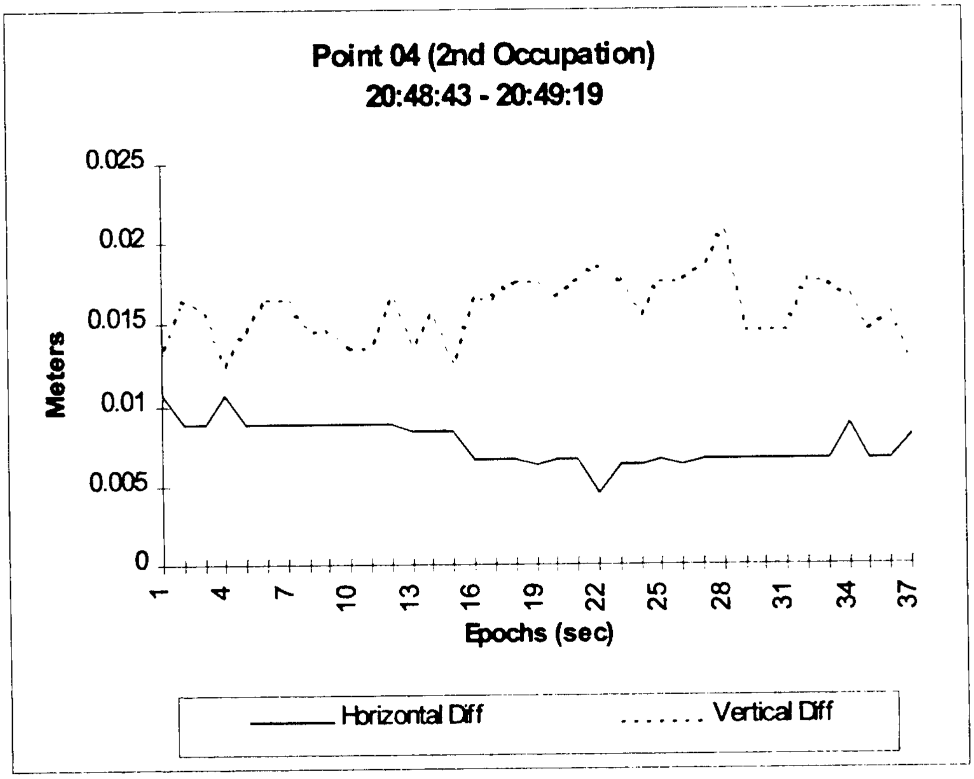
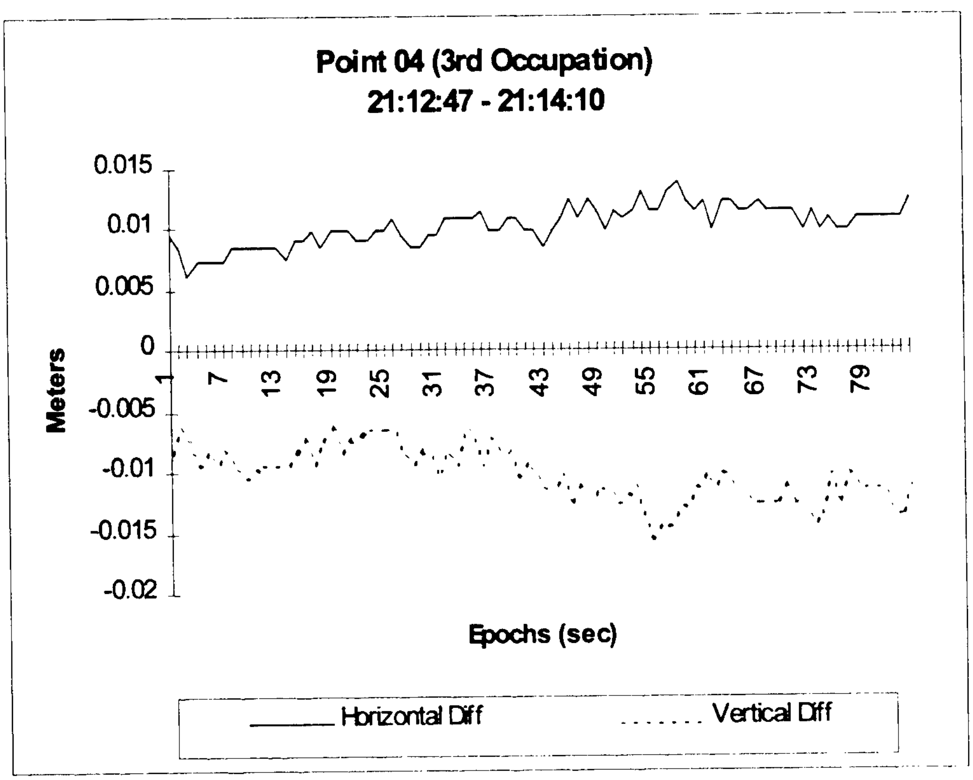
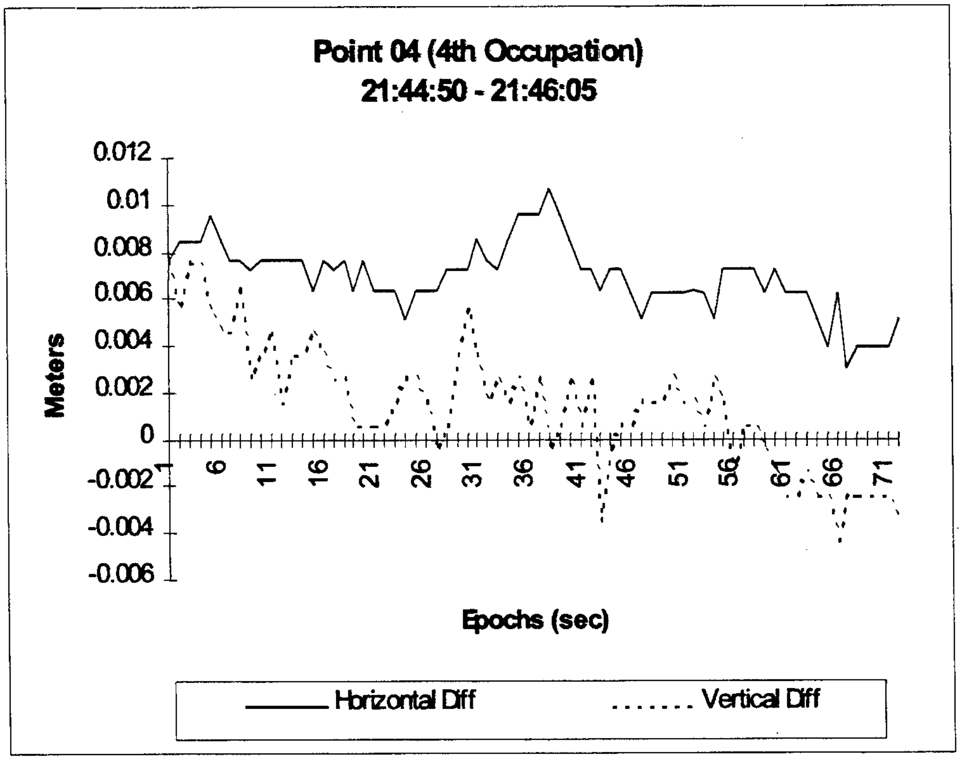
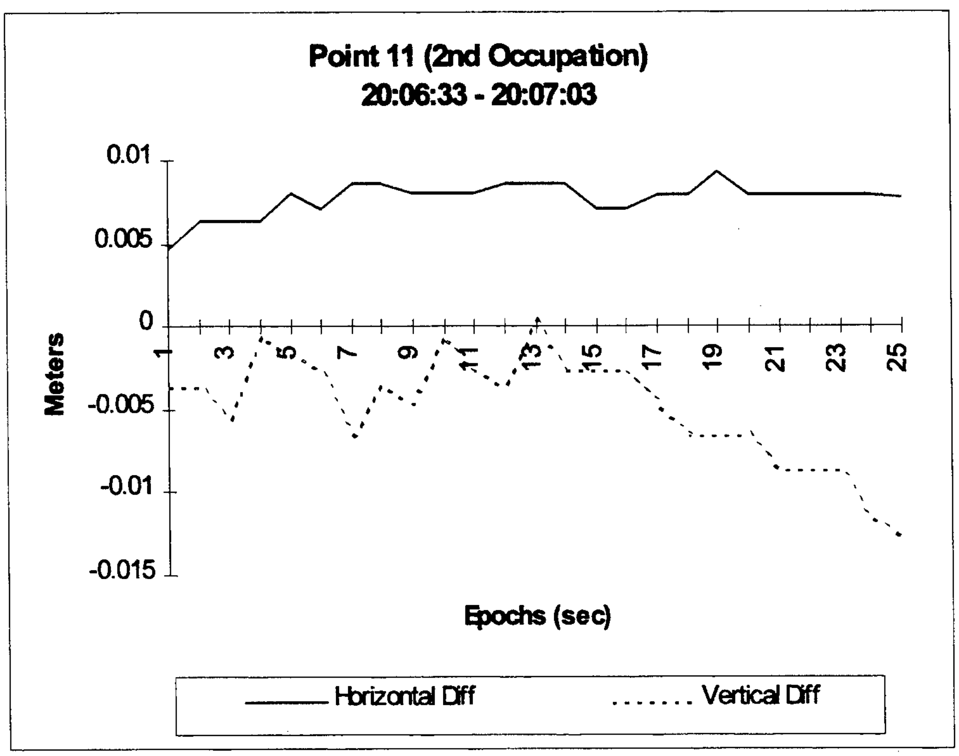
APPENDIX A

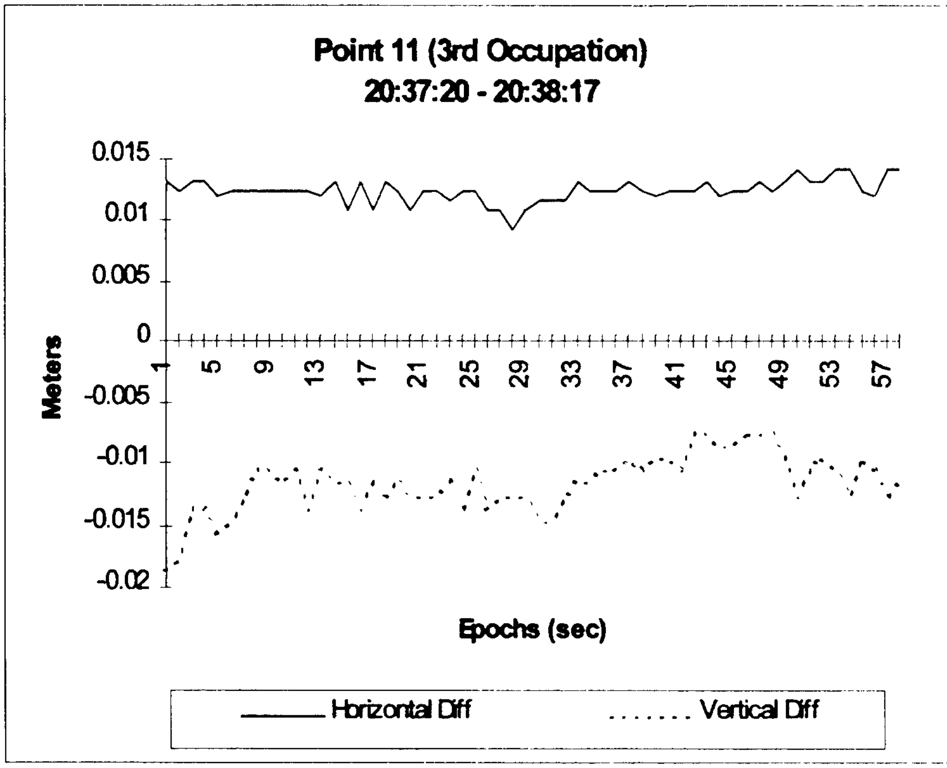
Repeatability Test Results (14 May 94)

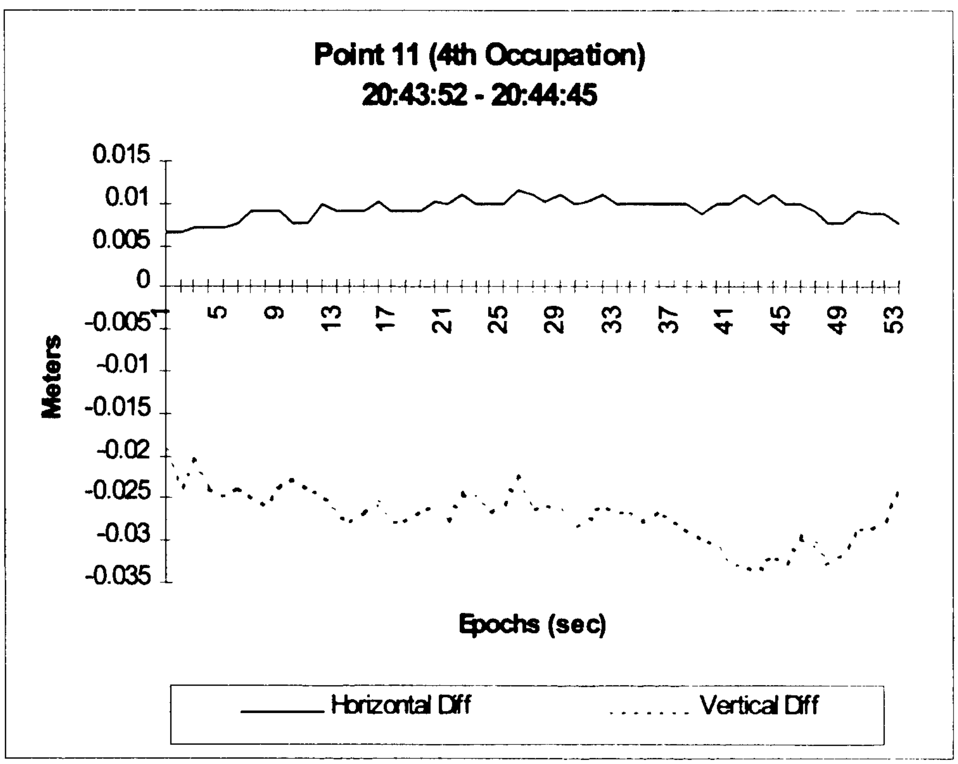


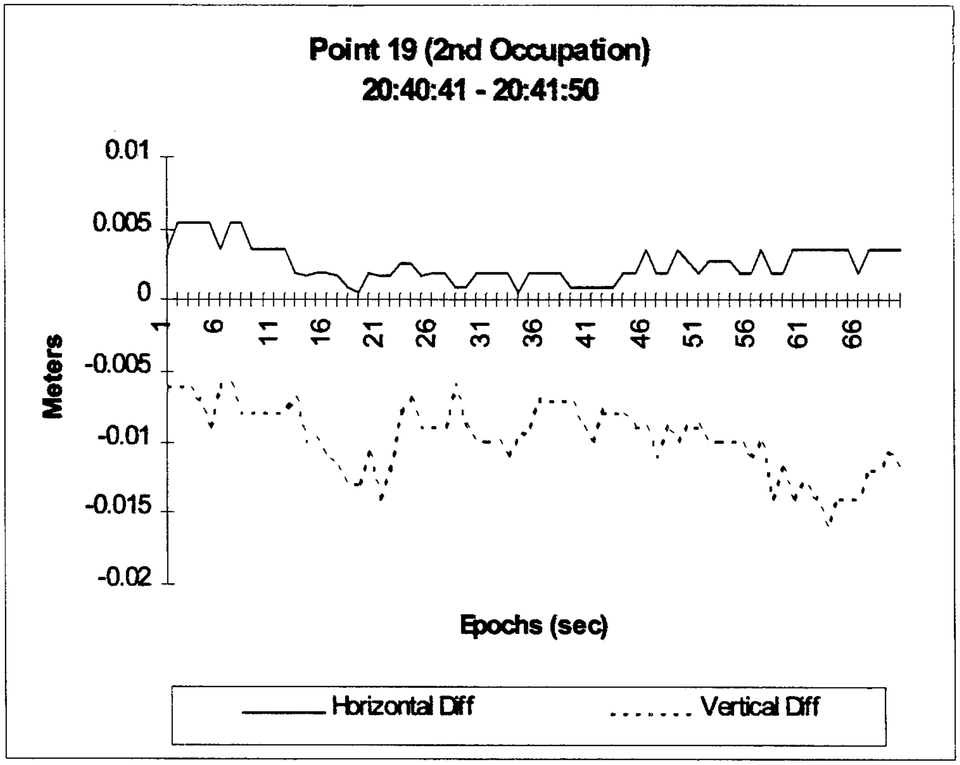


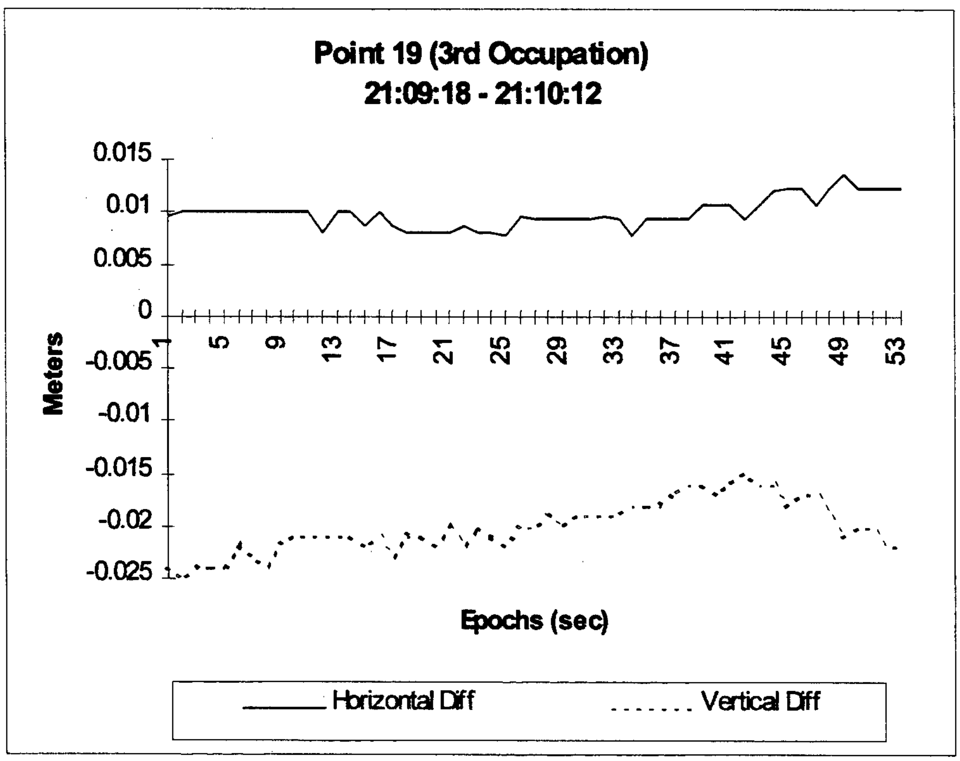

Point 04 (4th Occupation)
21:44:50 - 21:46:05
Meters
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
Epochs (sec)
Horizontal Diff
Vertical Diff

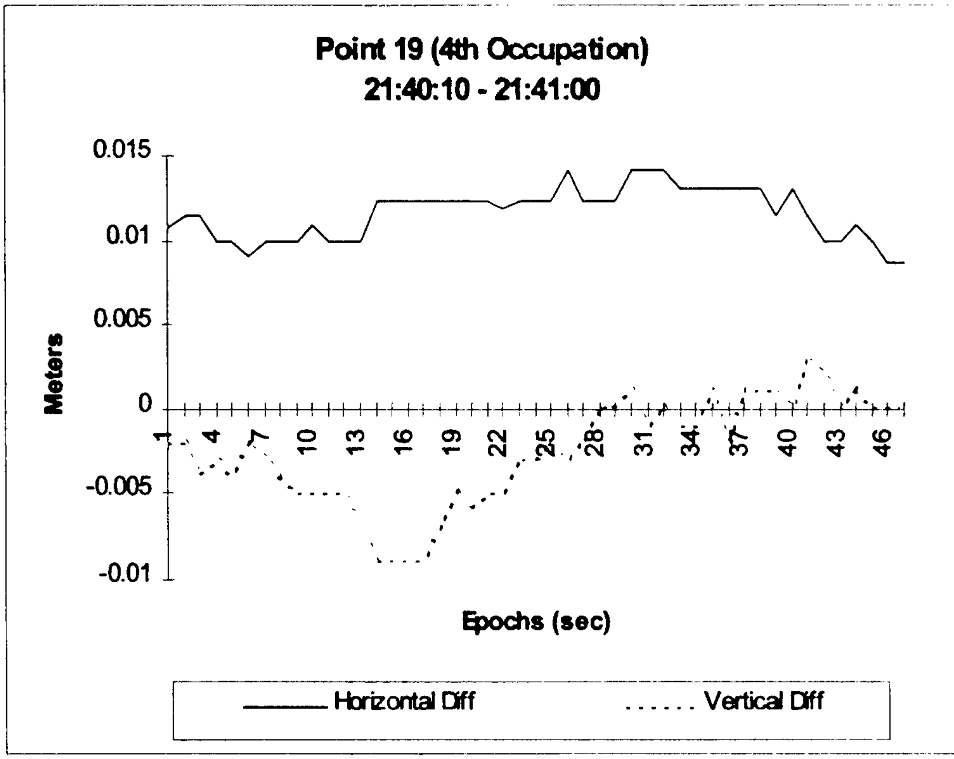

Point 11 (2nd Occupation)
20:06:33 - 20:07:03
Meters
0.01
0.005
0
-0.005
-0.01
-0.015
1
3
5
7
9
11
13
15
17
19
21
23
25
Epochs (sec)
Horizontal Diff
Vertical Diff

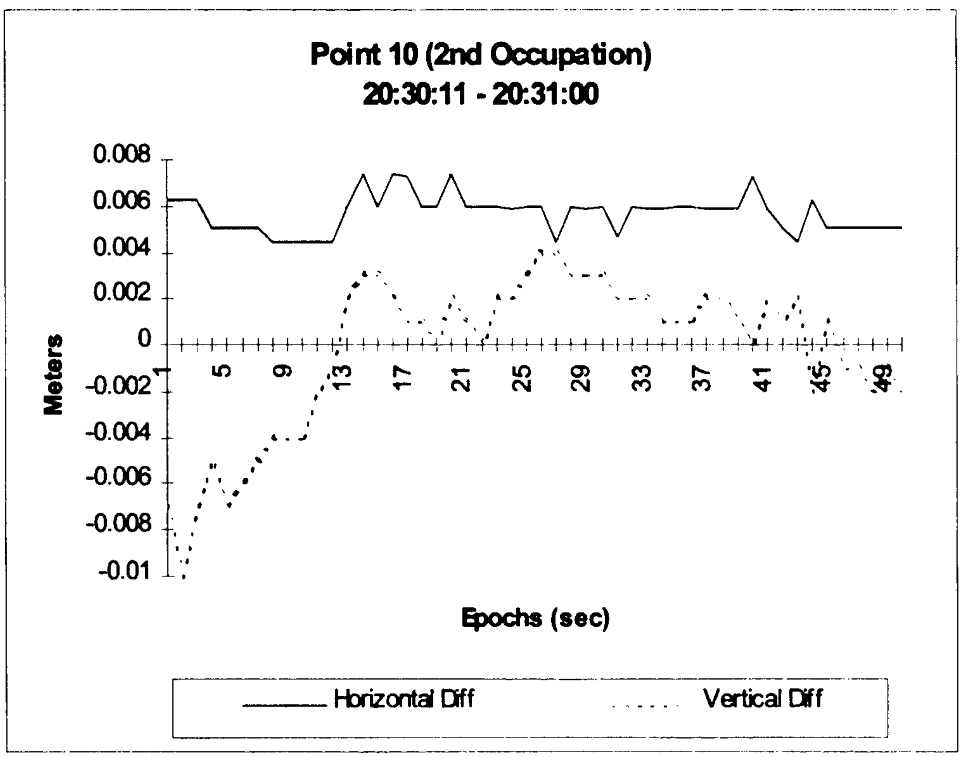

Point 11 (3rd Occupation)
20:37:20 - 20:38:17
Meters
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
Epochs (sec)
Horizontal Diff
Vertical Diff

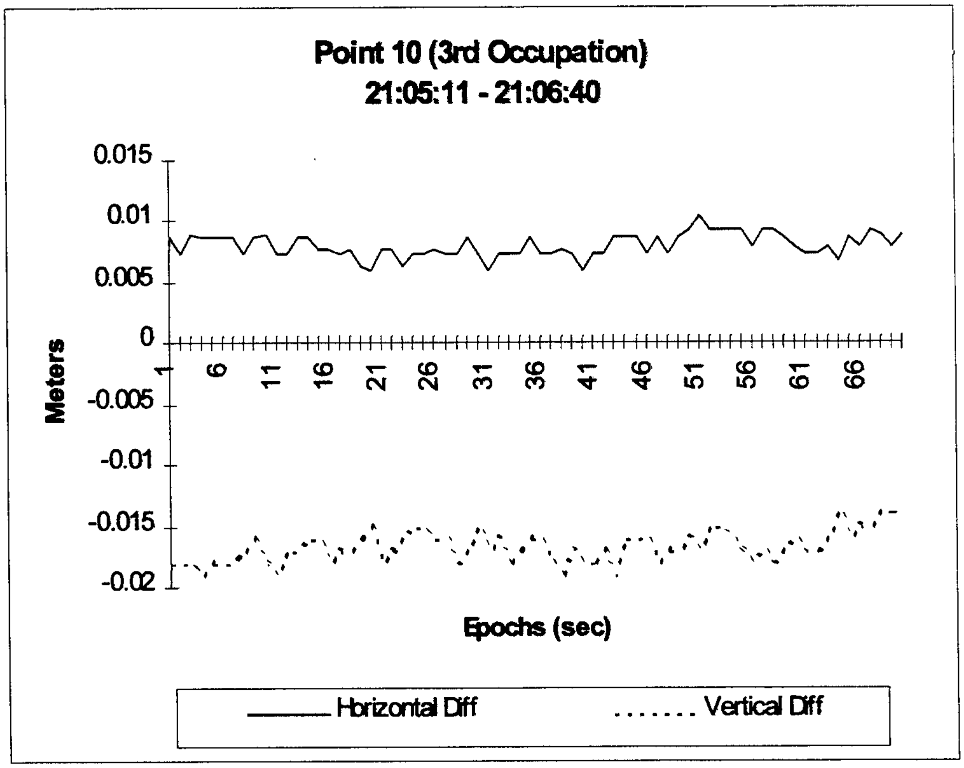

Point 11 (4th Occupation)
20:43:52 - 20:44:45
Meters
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
-0.035
1
5
9
13
17
21
25
29
33
37
41
45
49
53
Epochs (sec)
Horizontal Diff
Vertical Diff


Point 19 (2nd Occupation)
20:40:41 - 20:41:50
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Meters
1
6
11
16
21
26
31
36
41
46
51
56
61
66
Epochs (sec)
Horizontal Diff
Vertical Diff

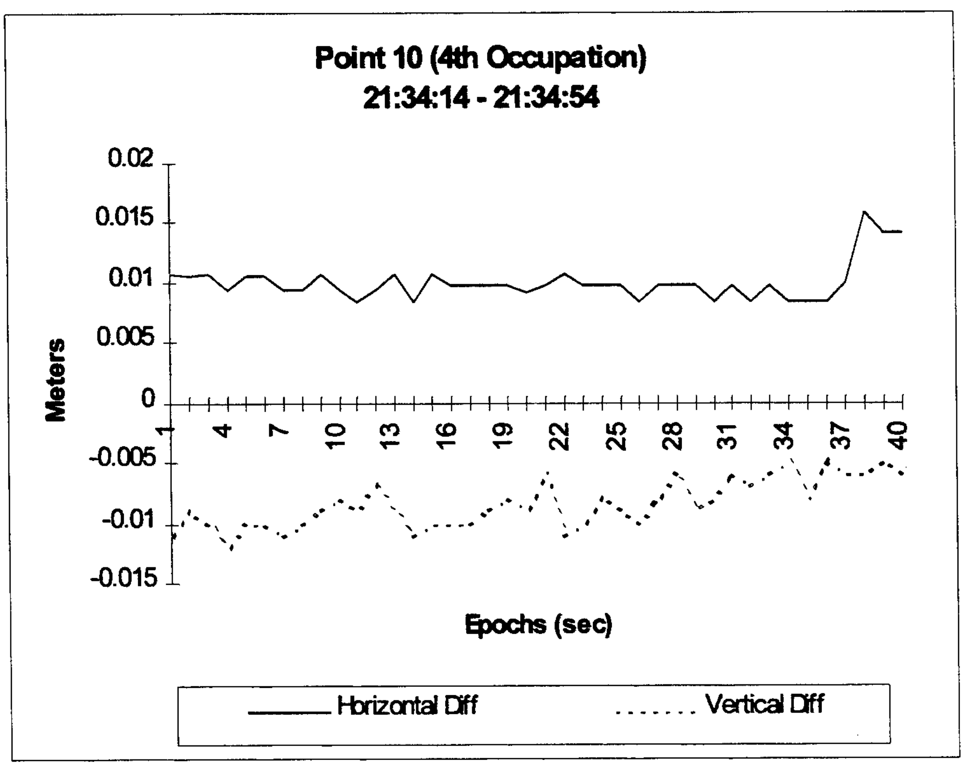

Point 19 (3rd Occupation)
21:09:18 - 21:10:12
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
Meters
1
5
9
13
17
21
25
29
33
37
41
45
49
53
Epochs (sec)
Horizontal Diff
Vertical Diff


Point 19 (4th Occupation)
21:40:10 - 21:41:00
0.015
0.01
0.005
0
-0.005
-0.01
Meters
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
Epochs (sec)
Horizontal Diff
Vertical Diff


Point 10 (2nd Occupation)
20:30:11 - 20:31:00
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
Meters
1
5
9
13
17
21
25
29
33
37
41
45
49
Epochs (sec)
Horizontal Diff
Vertical Diff



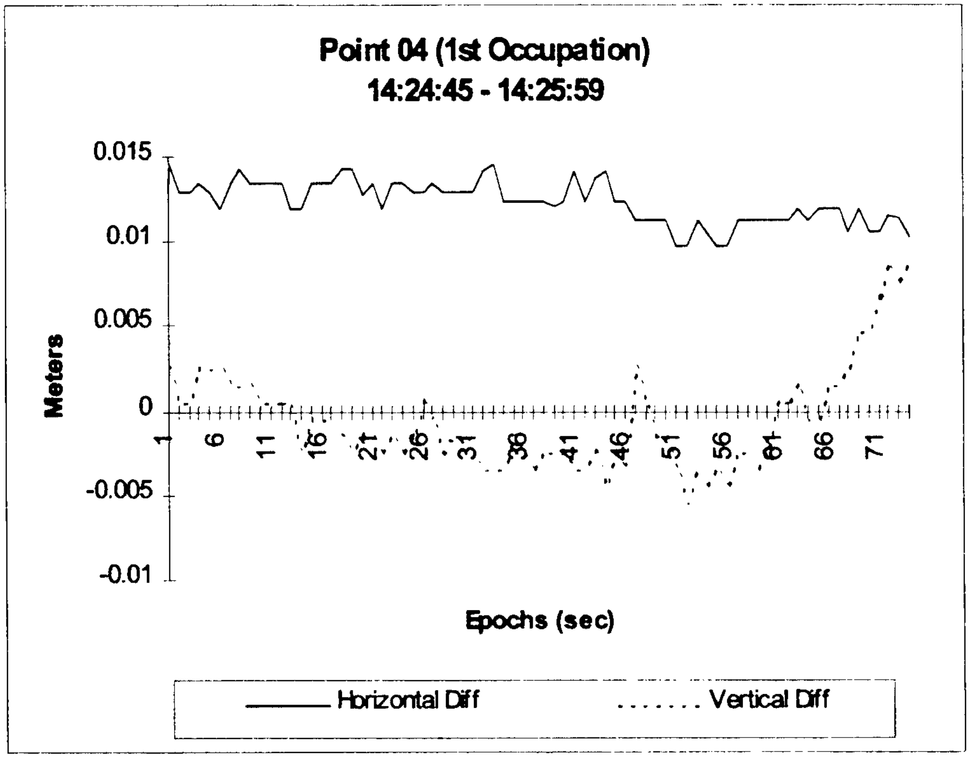
Point 10 (3rd Occupation)
21:05:11 - 21:06:40
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Meters
1
6
11
16
21
26
31
36
41
46
51
56
61
66
Epochs (sec)
Horizontal Diff
Vertical Diff

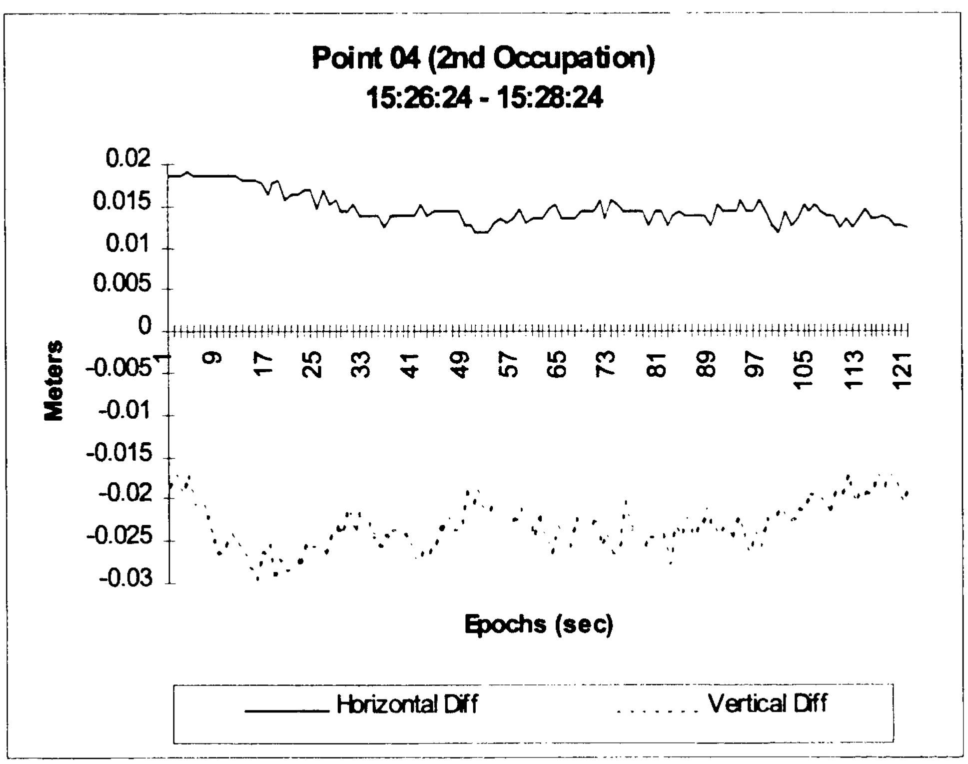


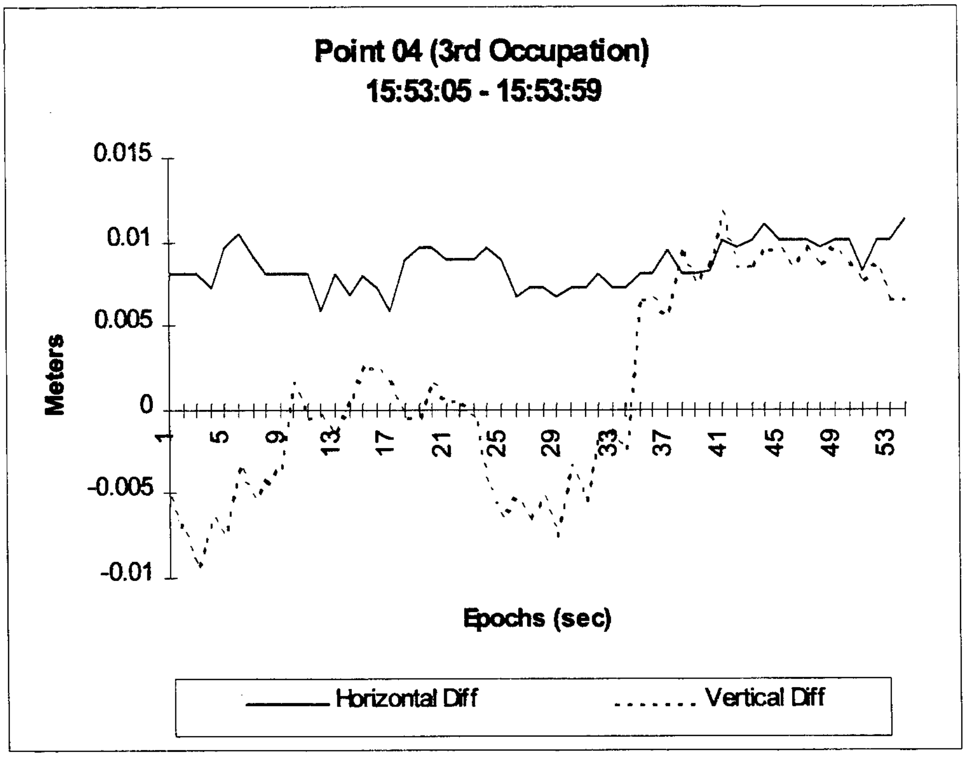
Point 10 (4th Occupation)
21:34:14 - 21:34:54
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Meters
1
4
7
10
13
16
19
22
25
28
31
34
37
40
Epochs (sec)
Horizontal Diff
Vertical Diff

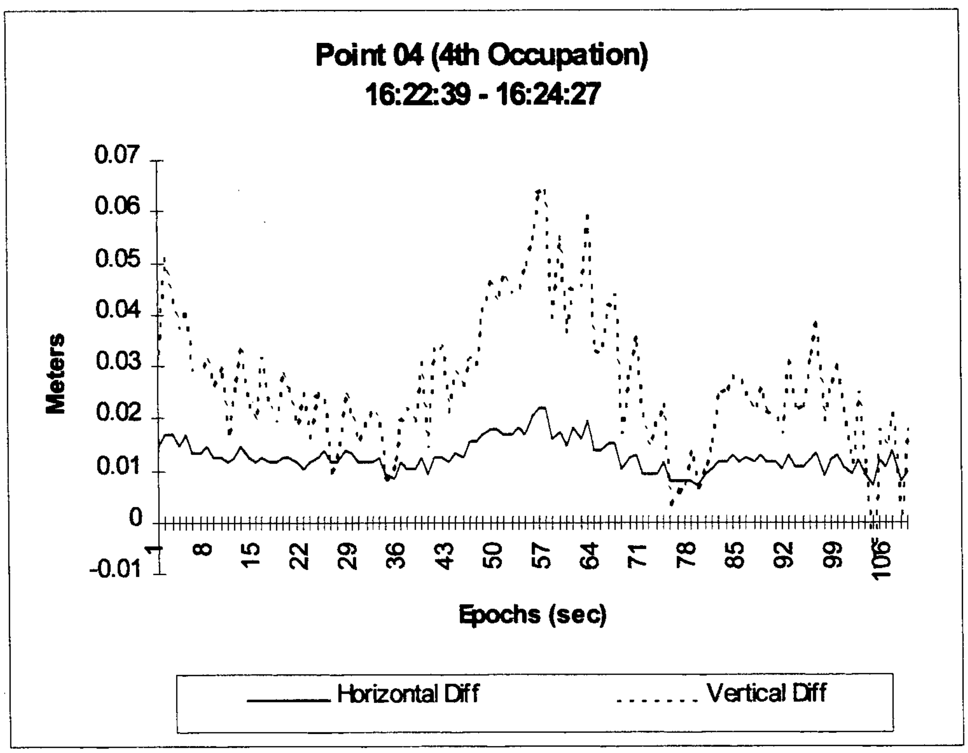
APPENDIX B

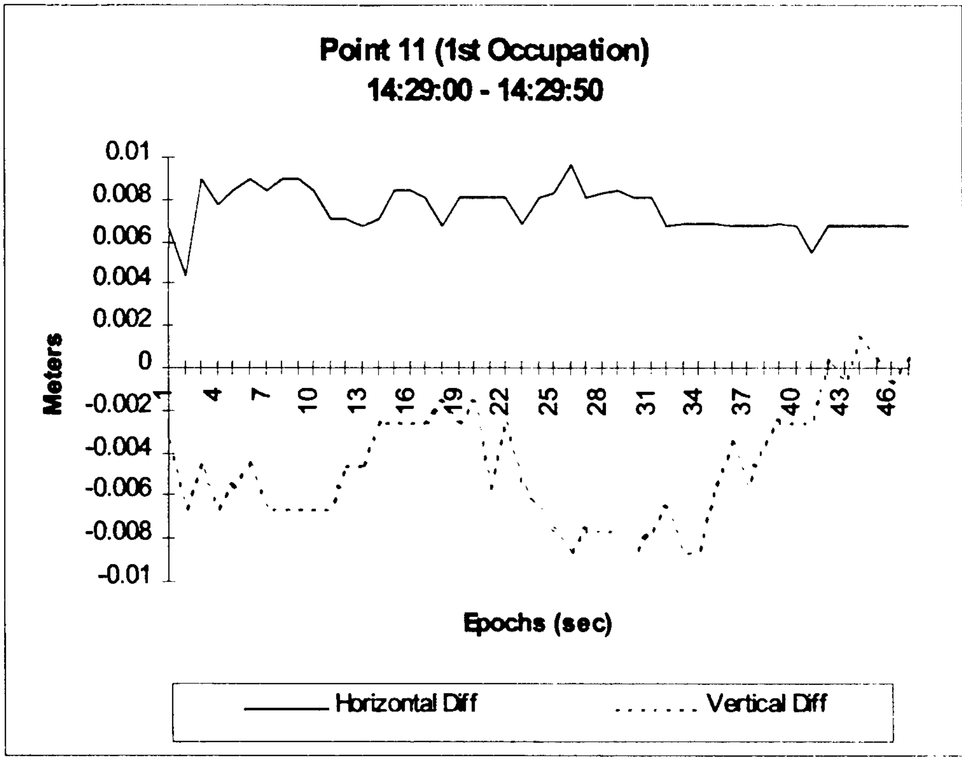
Repeatability Test Results (15 May 94)

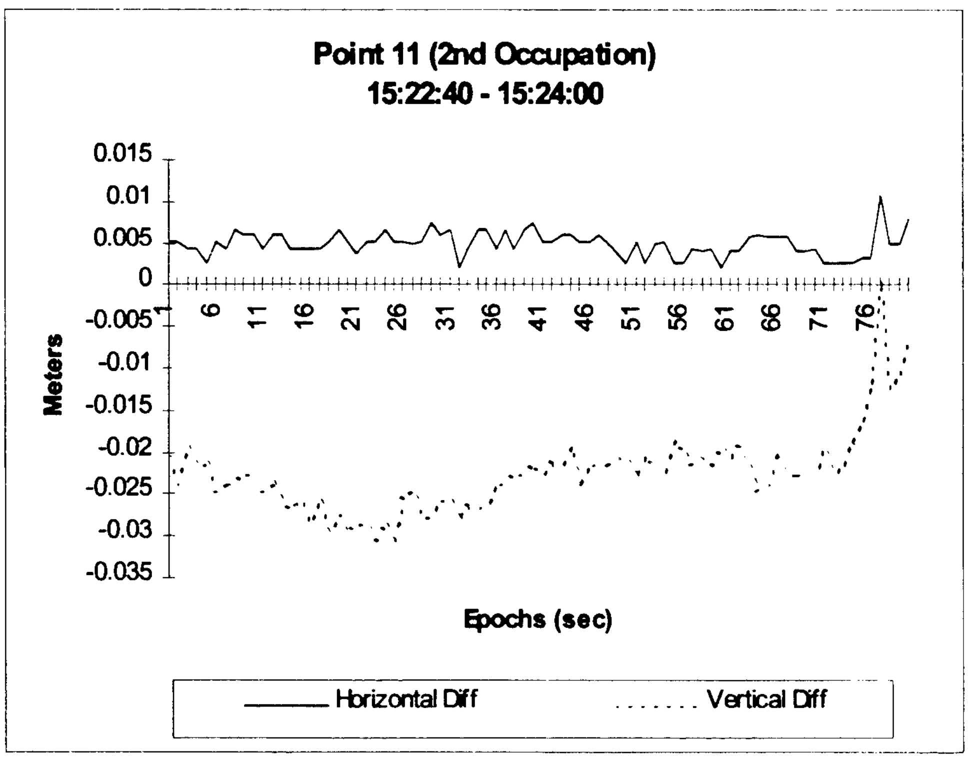


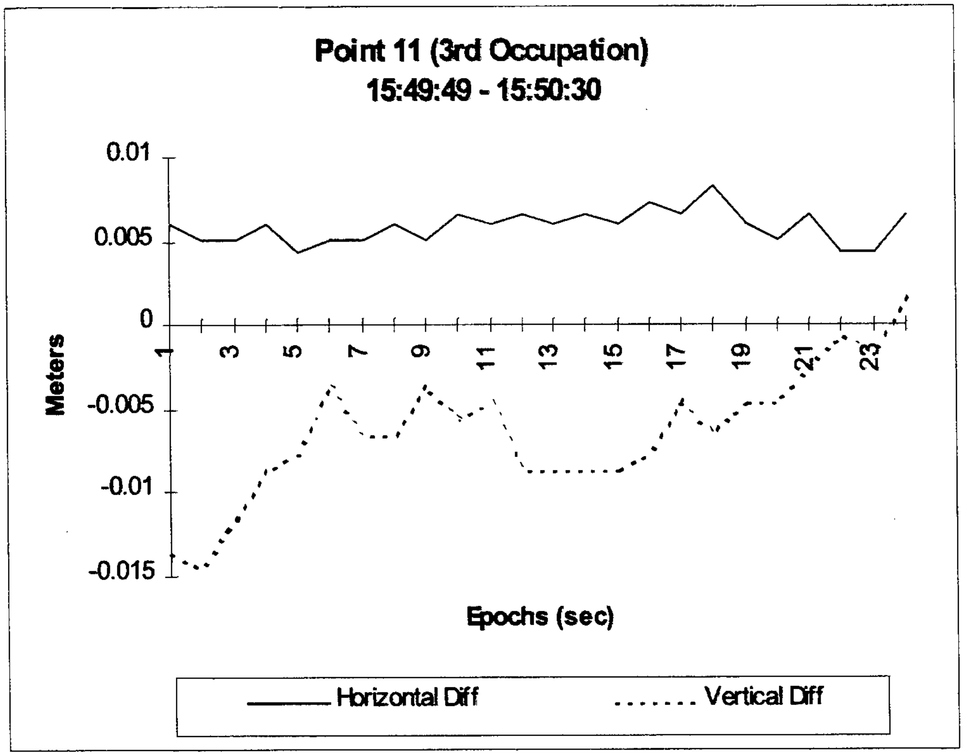



Point 04 (3rd Occupation)
15:53:05 - 15:53:59
0.015
0.01
0.005
0
-0.005
-0.01
Meters
1
5
9
13
17
21
25
29
33
37
41
45
49
53
Epochs (sec)
Horizontal Diff
Vertical Diff

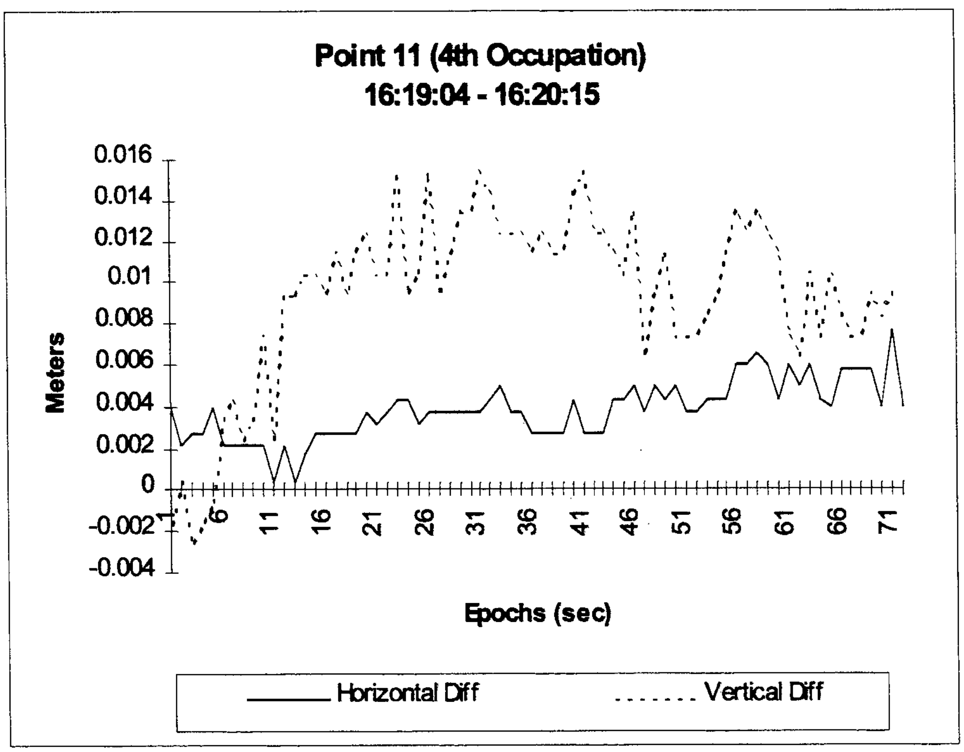

Point 04 (4th Occupation)
16:22:39 - 16:24:27
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
Meters
1
8
15
22
29
36
43
50
57
64
71
78
85
92
99
106
Epochs (sec)
Horizontal Diff
Vertical Diff


Point 11 (1st Occupation)
14:29:00 - 14:29:50
Meters
Epochs (sec)
Horizontal Diff
Vertical Diff

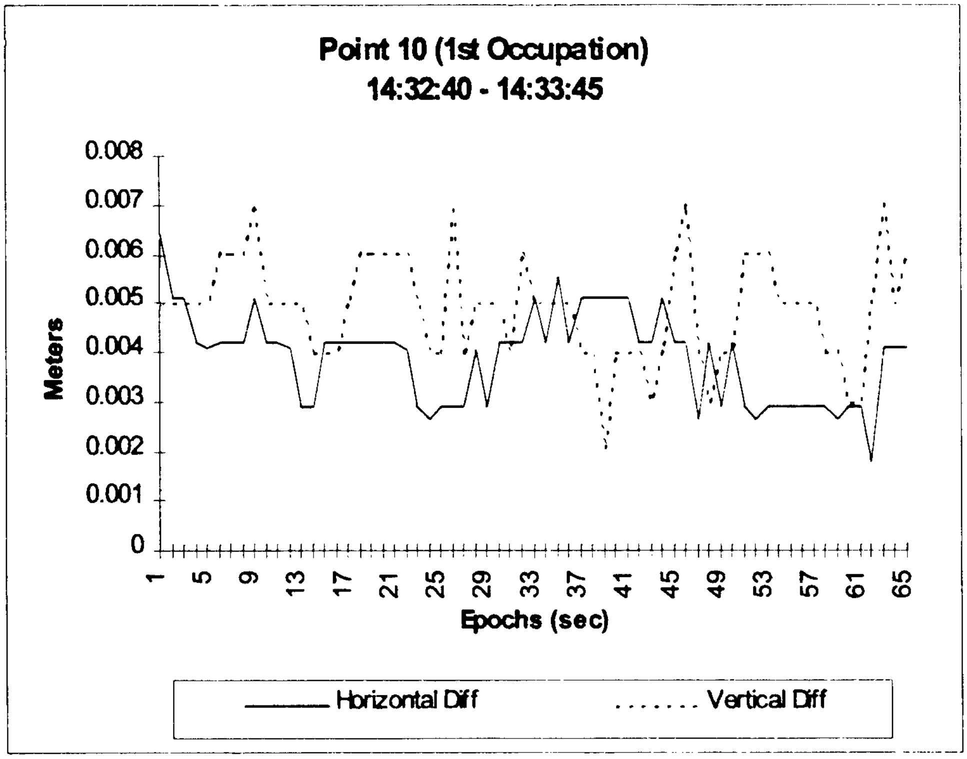

Point 11 (2nd Occupation)
15:22:40 - 15:24:00
Meters
Epochs (sec)
Horizontal Diff
Vertical Diff

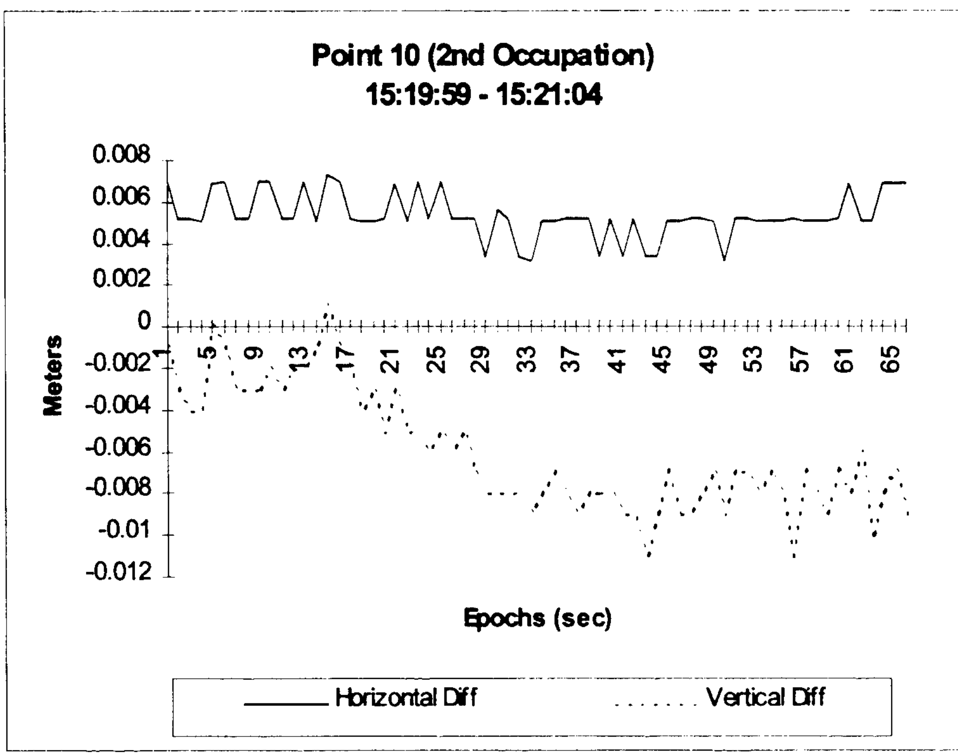


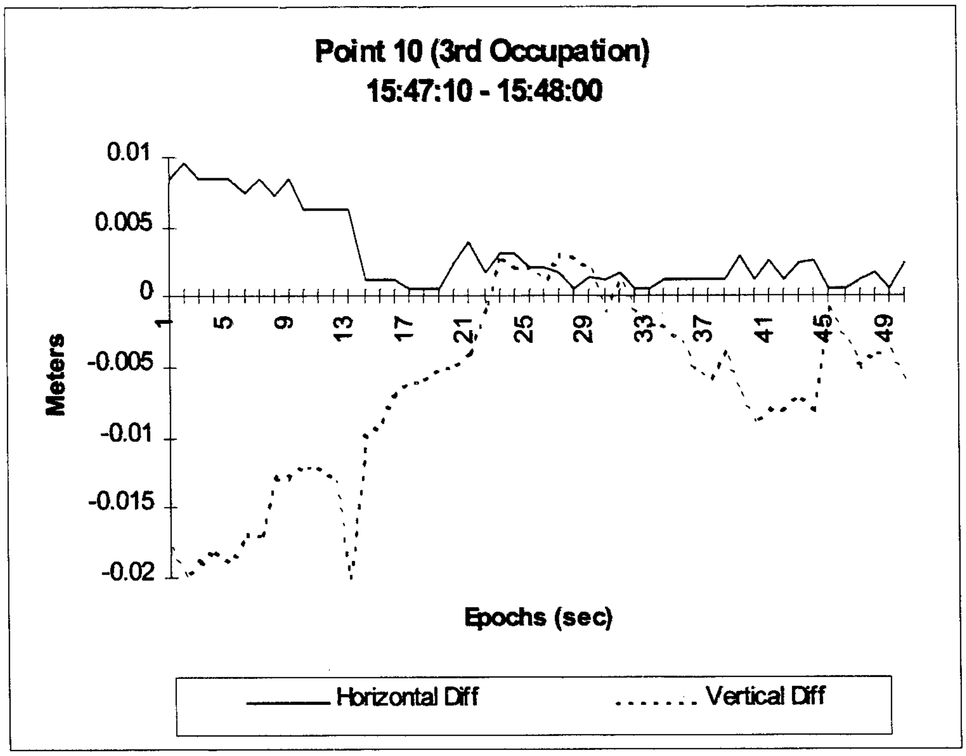
Point 11 (3rd Occupation)
15:49:49 - 15:50:30
0.01
0.005
0
-0.005
-0.01
-0.015
Meters
1
3
5
7
9
11
13
15
17
19
21
23
Epochs (sec)
Horizontal Diff
Vertical Diff

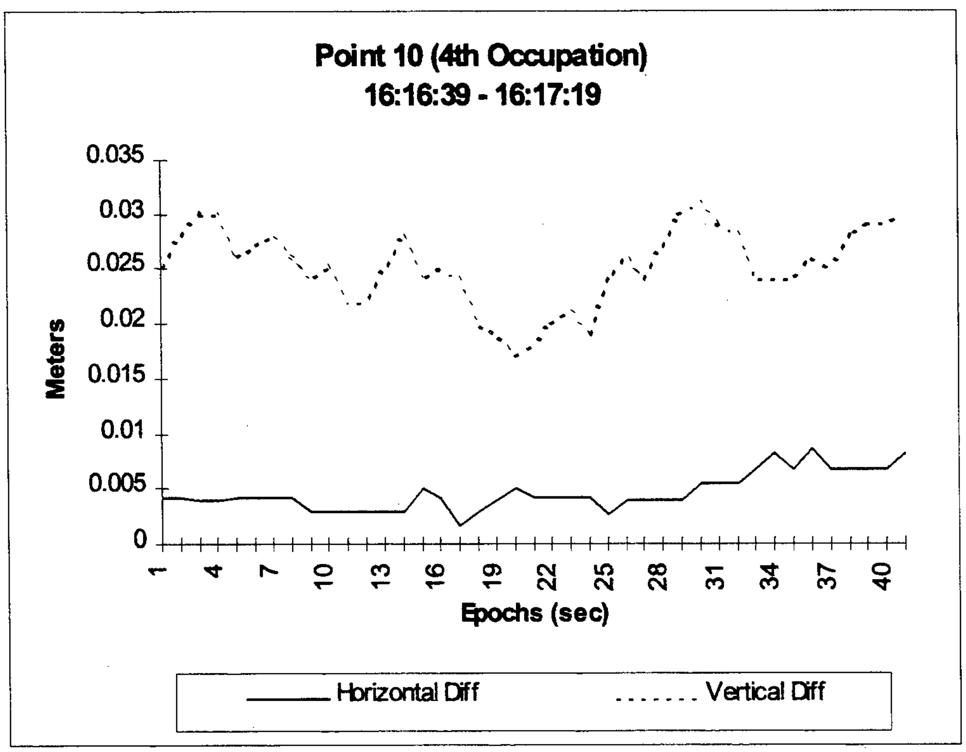


Point 11 (4th Occupation)
16:19:04 - 16:20:15
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
Meters
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
Epochs (sec)
Horizontal Diff
Vertical Diff


Point 10 (1st Occupation)
14:32:40 - 14:33:45
Meters
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65
Epochs (sec)
Horizontal Diff
Vertical Diff

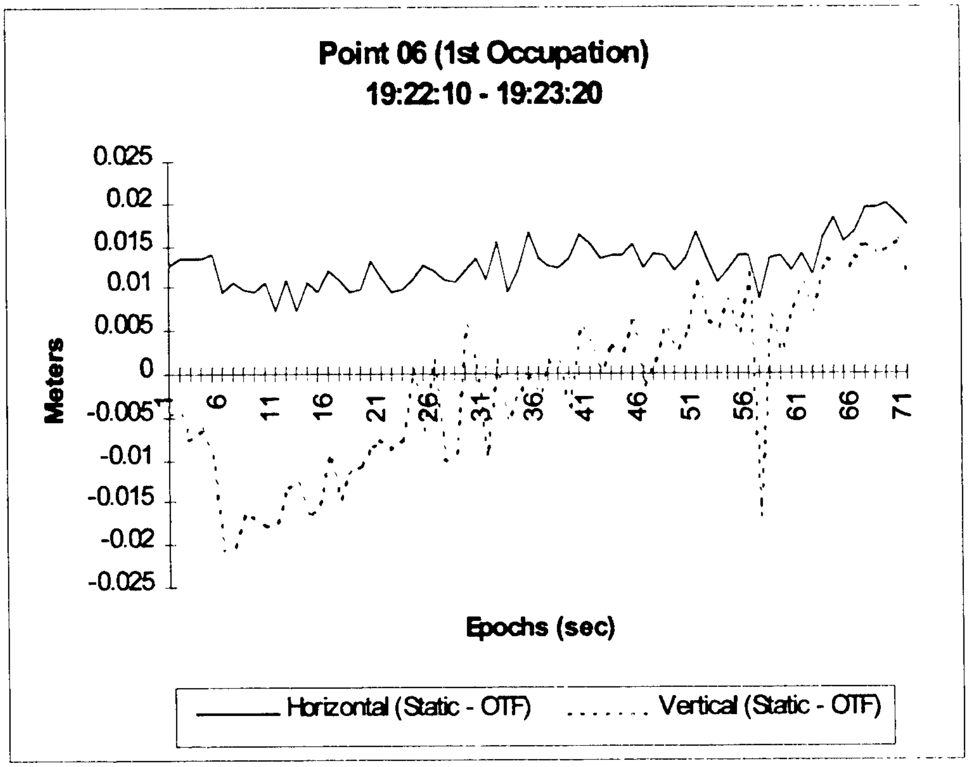

Point 10 (2nd Occupation)
15:19:59 - 15:21:04
Meters
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65
Epochs (sec)
Horizontal Diff
Vertical Diff

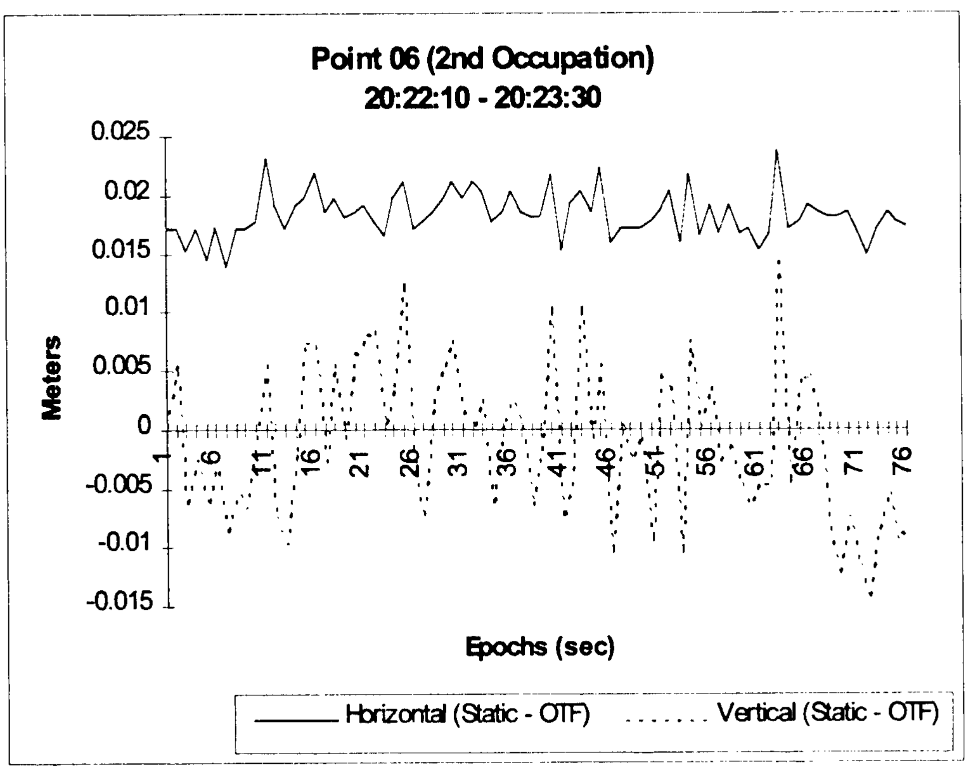

Point 10 (3rd Occupation)
15:47:10 - 15:48:00
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Meters
1
5
9
13
17
21
25
29
33
37
41
45
49
Epochs (sec)
Horizontal Diff
Vertical Diff

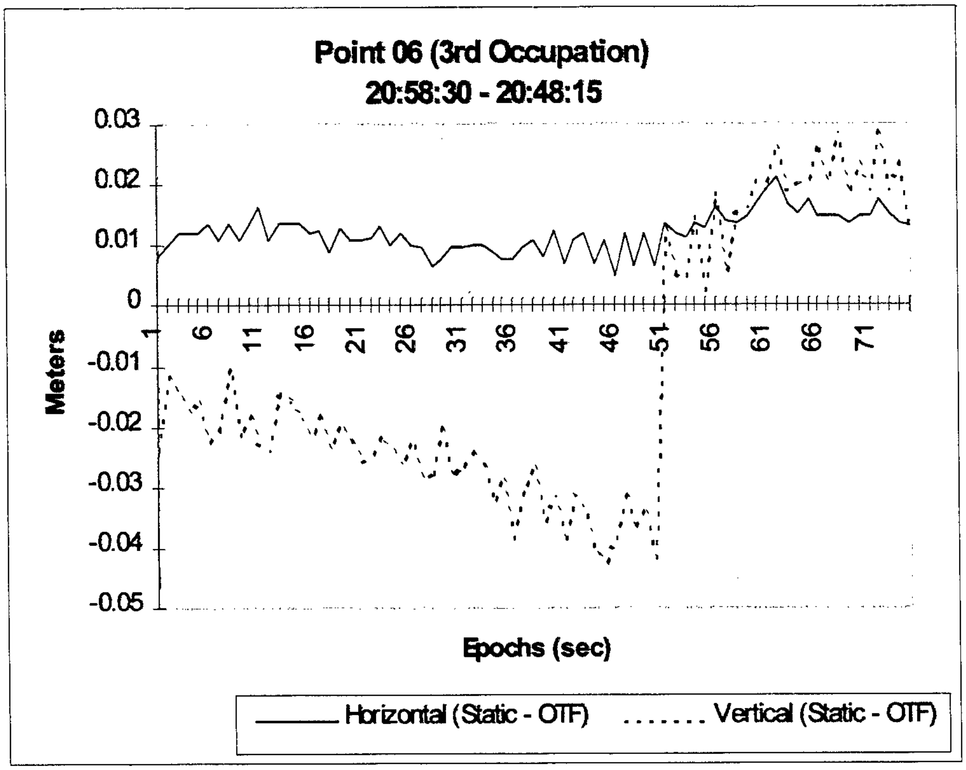

Point 10 (4th Occupation)
16:16:39 - 16:17:19
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Meters
1
4
7
10
13
16
19
22
25
28
31
34
37
40
Epochs (sec)
Horizontal Diff
Vertical Diff

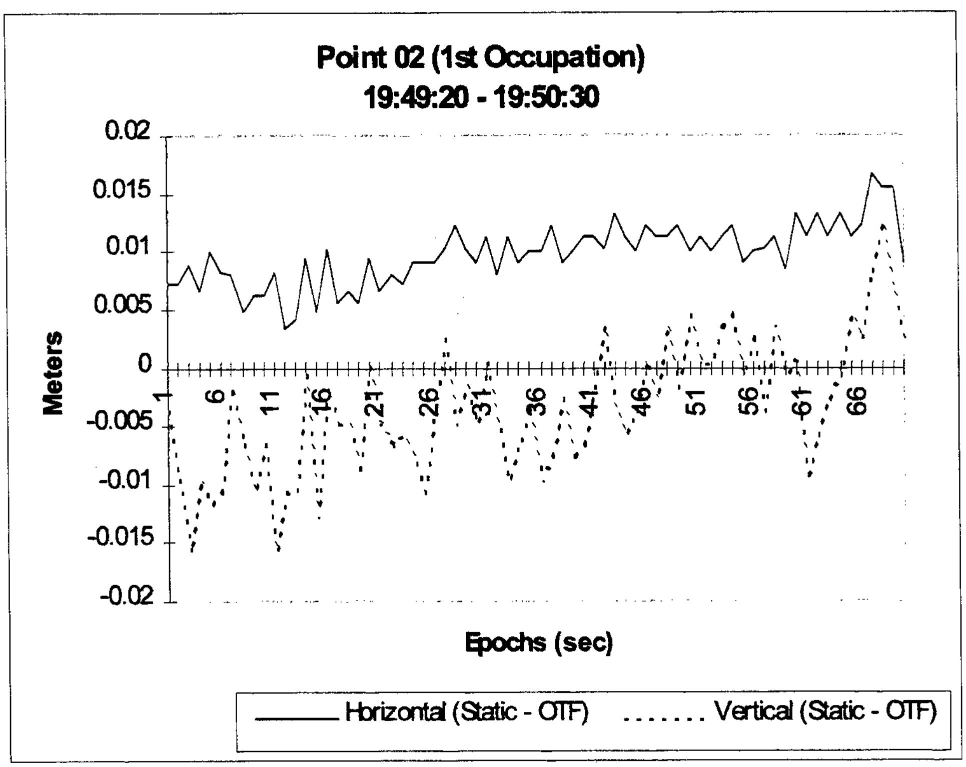
APPENDIX C

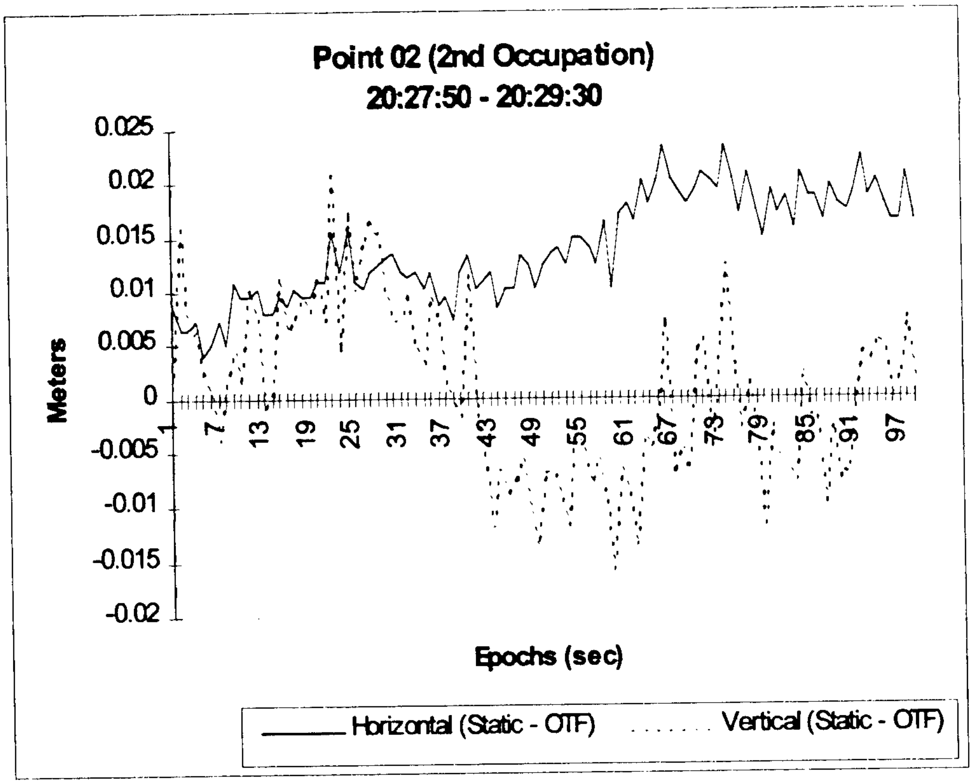
Repeatability Test Results (27 May 96)

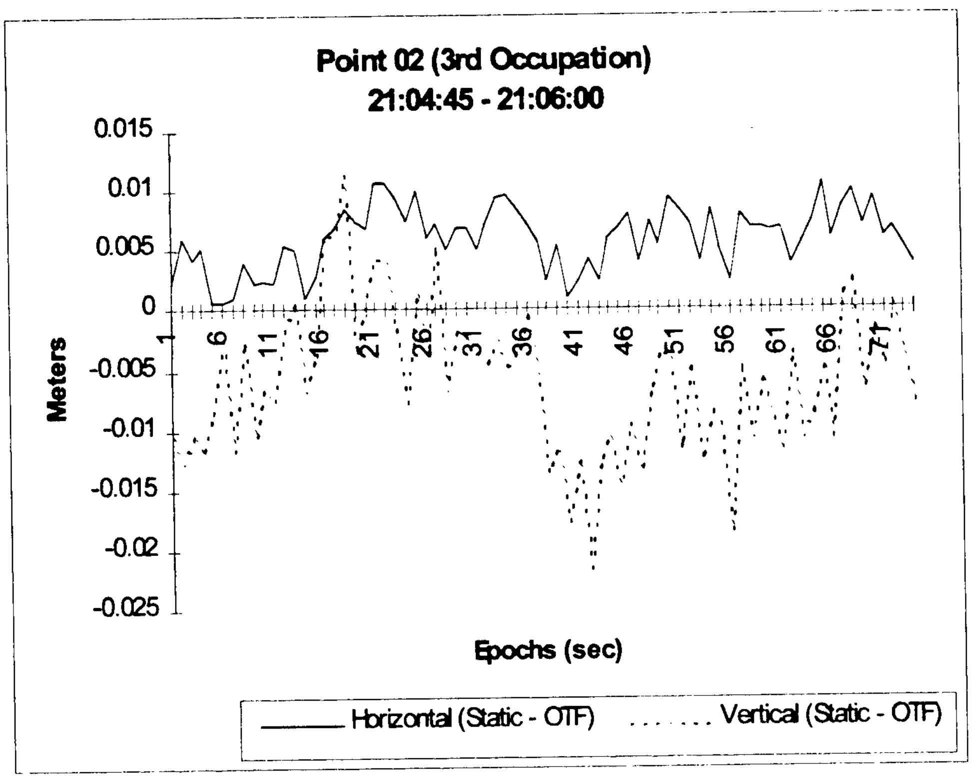


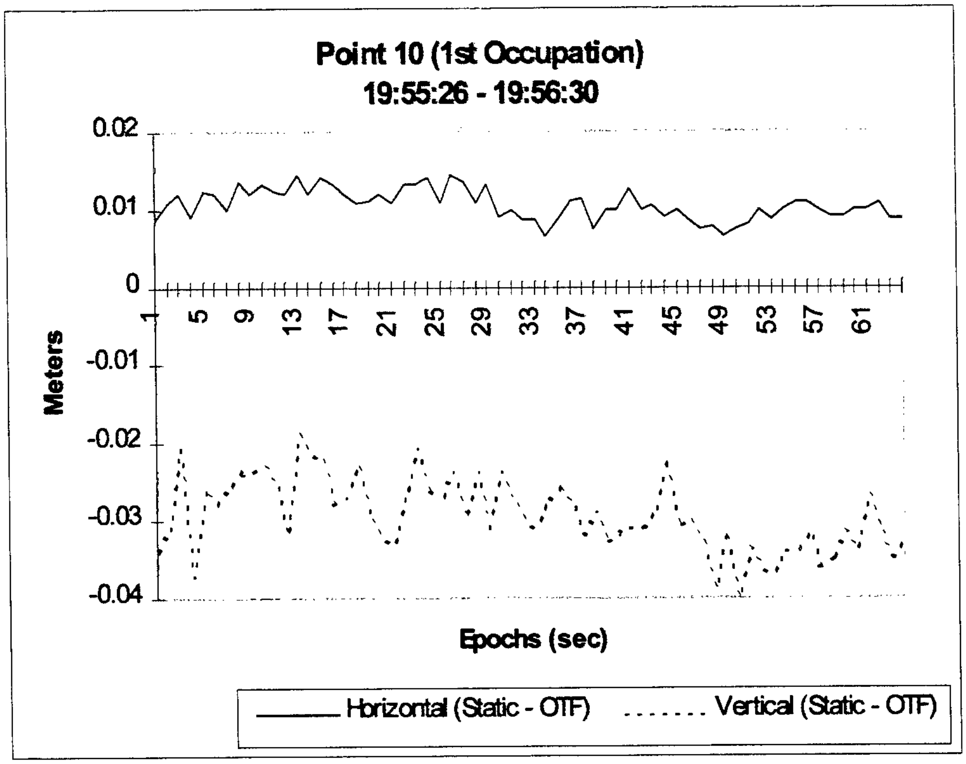


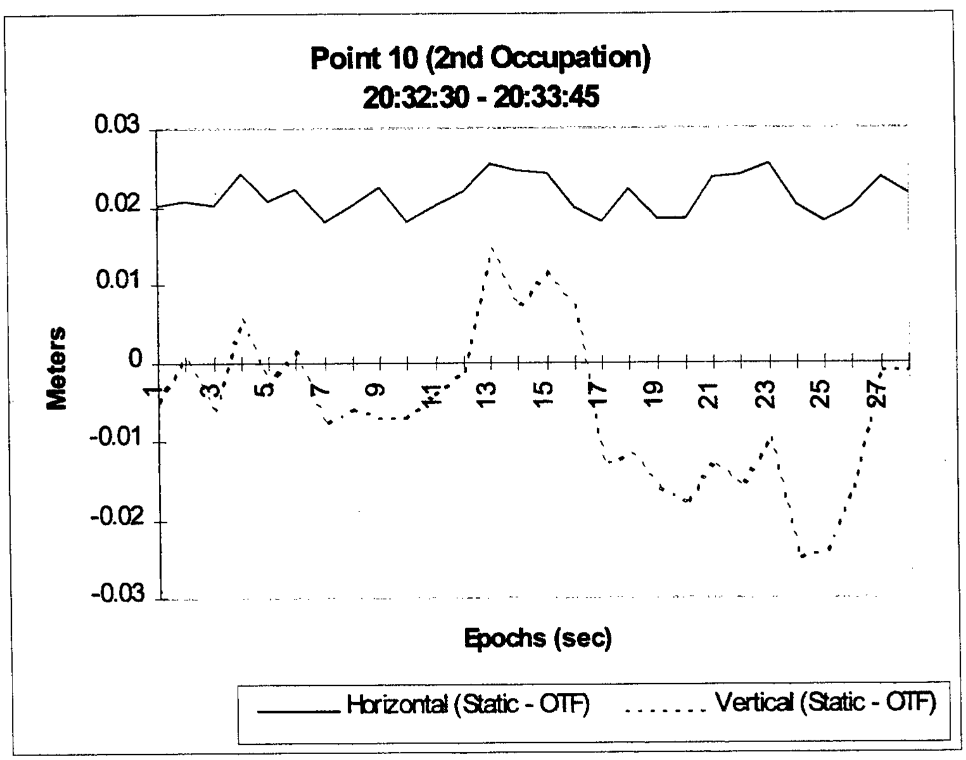

Point 06 (3rd Occupation)
20:58:30 - 20:48:15
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Meters
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

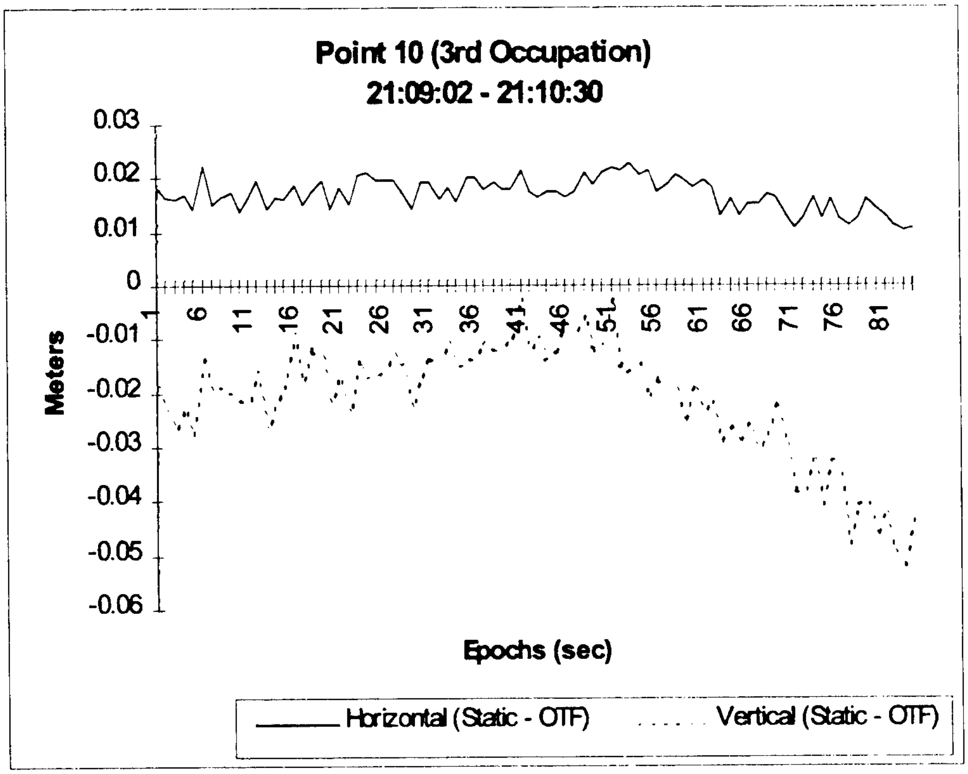

Point 02 (1st Occupation)
19:49:20 - 19:50:30
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Meters
1
6
11
16
21
26
31
36
41
46
51
56
61
66
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

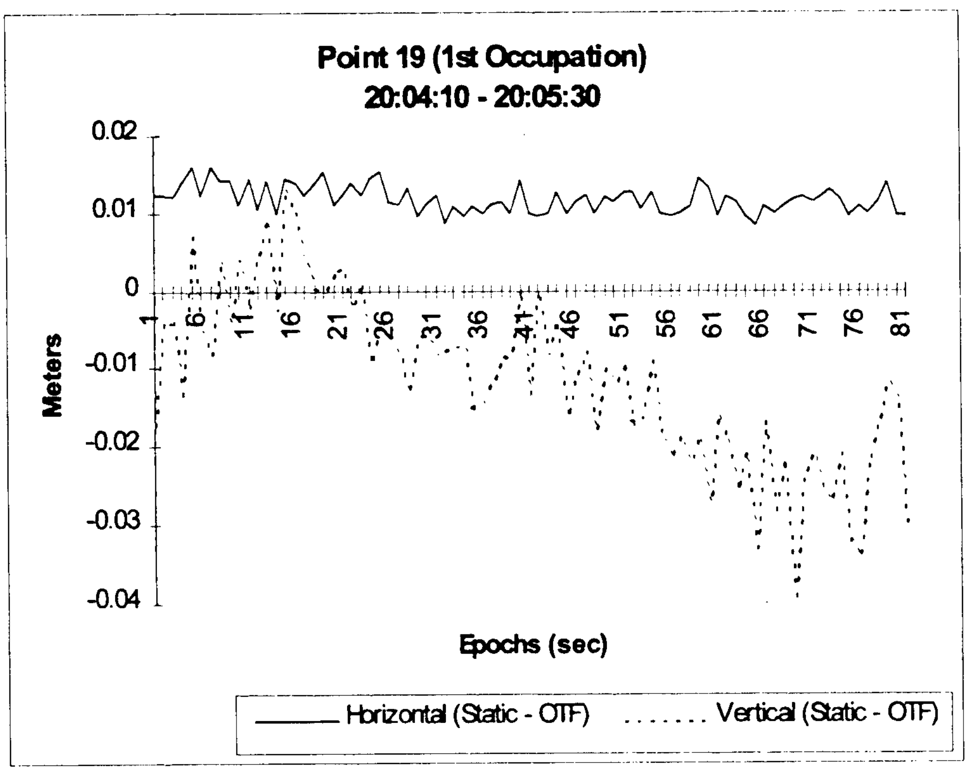

Point 02 (2nd Occupation)
20:27:50 - 20:29:30
Meters
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

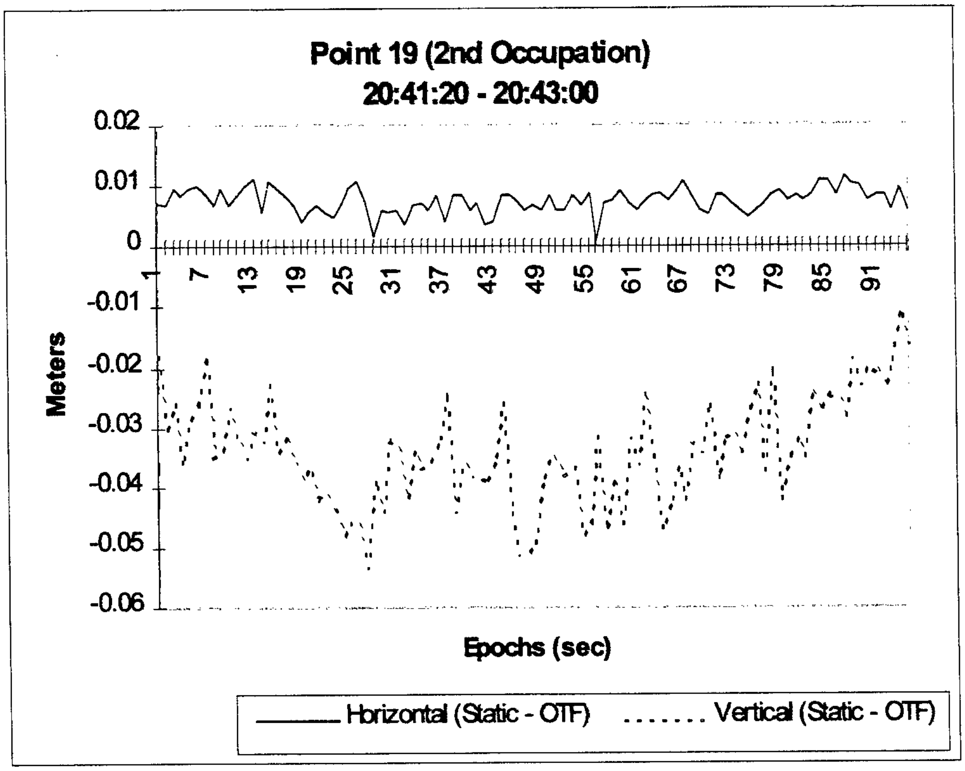

Point 02 (3rd Occupation)
21:04:45 - 21:06:00
Meters
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

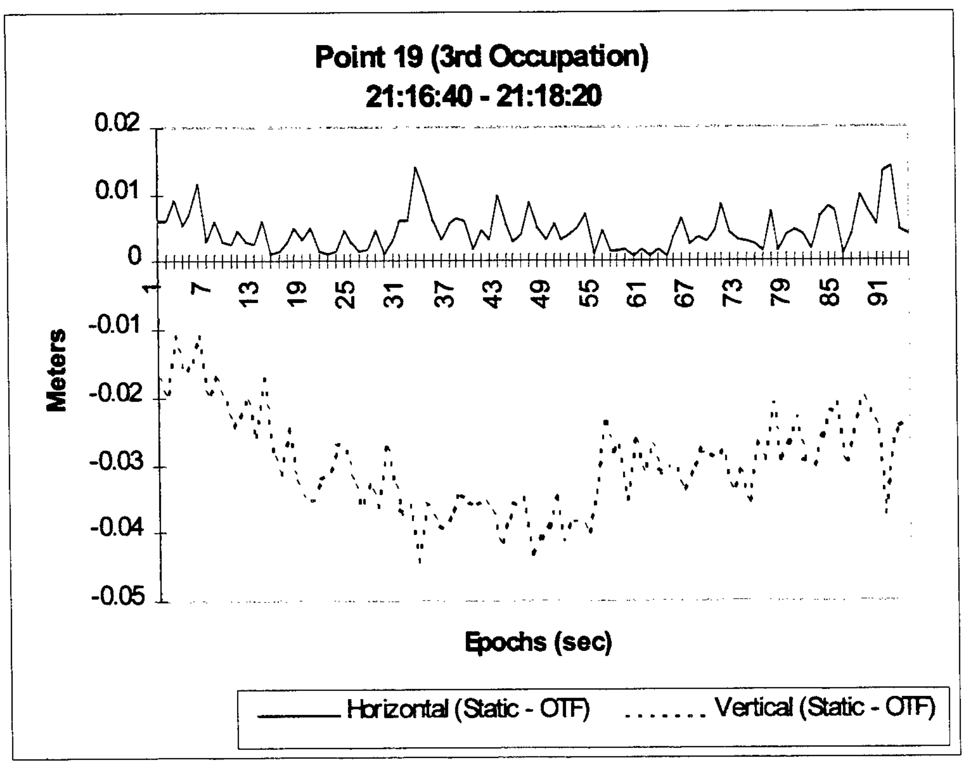

Point 10 (1st Occupation)
19:55:26 - 19:56:30
Meters
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

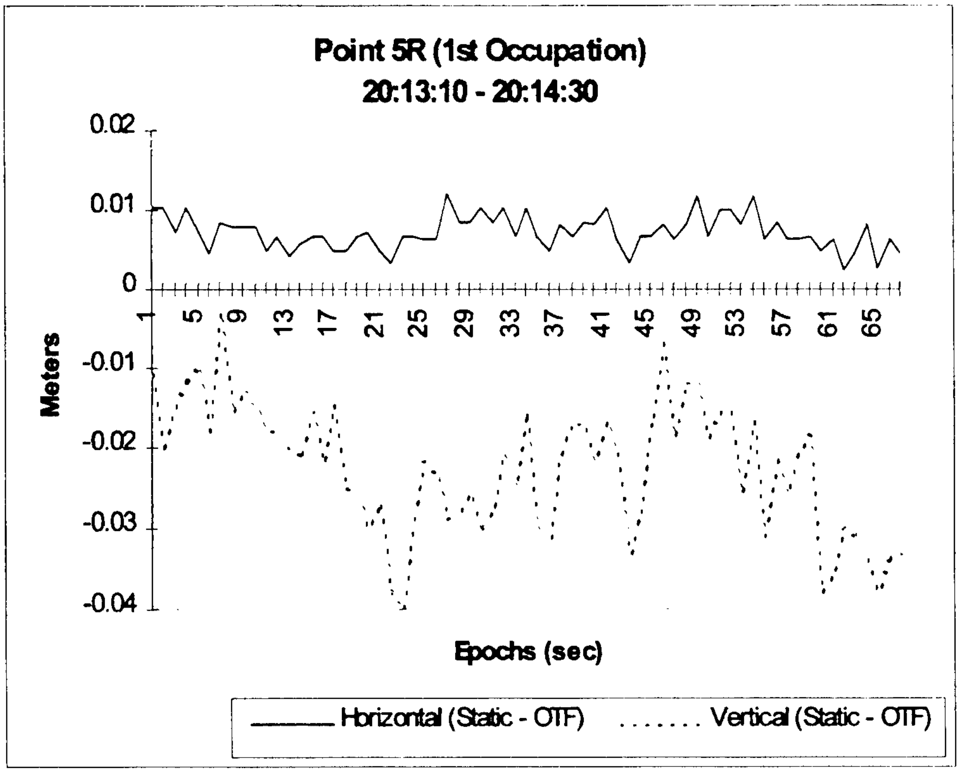

Point 10 (2nd Occupation)
20:32:30 - 20:33:45
Meters
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
1
3
5
7
9
11
13
15
17
19
21
23
25
27
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)


Point 10 (3rd Occupation)
21:09:02 - 21:10:30
Meters
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

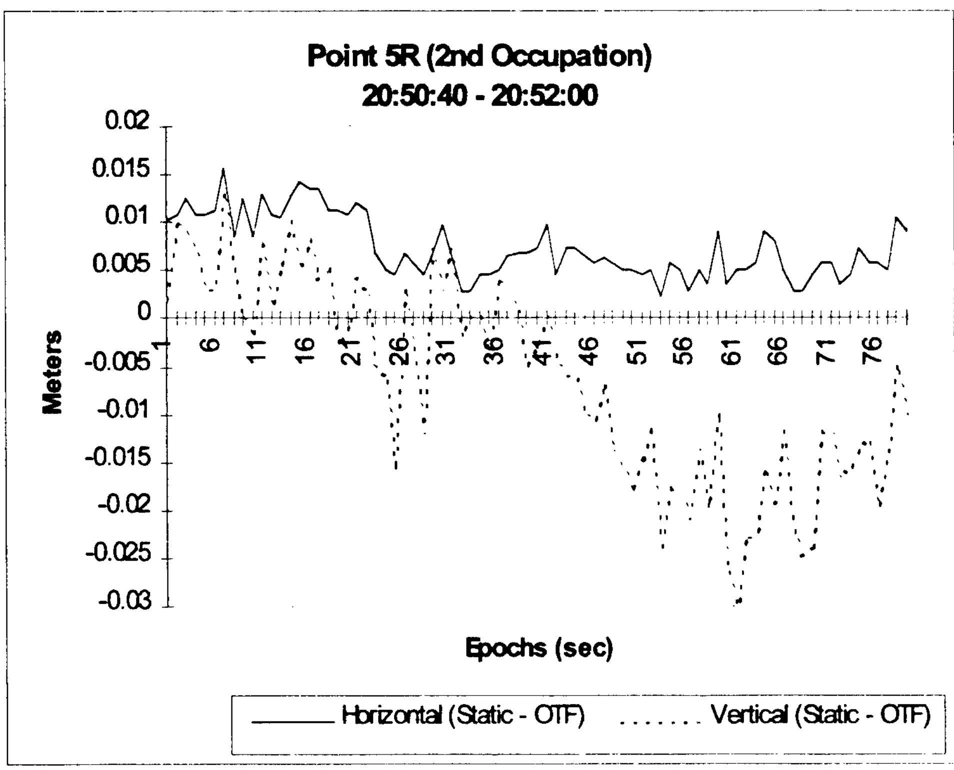

Point 19 (1st Occupation)
20:04:10 - 20:05:30
Meters
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)


Point 19 (2nd Occupation)
20:41:20 - 20:43:00
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
Meters
1
7
13
19
25
31
37
43
49
55
61
67
73
79
85
91
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

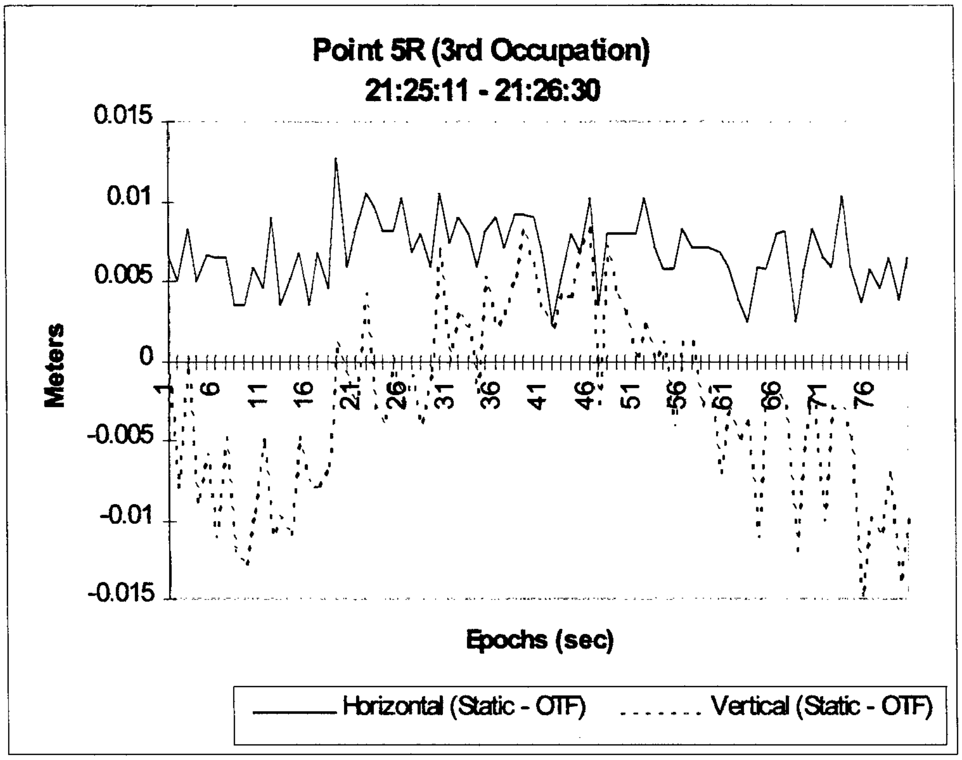

Point 19 (3rd Occupation)
21:16:40 - 21:18:20
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Meters
1
7
13
19
25
31
37
43
49
55
61
67
73
79
85
91
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)



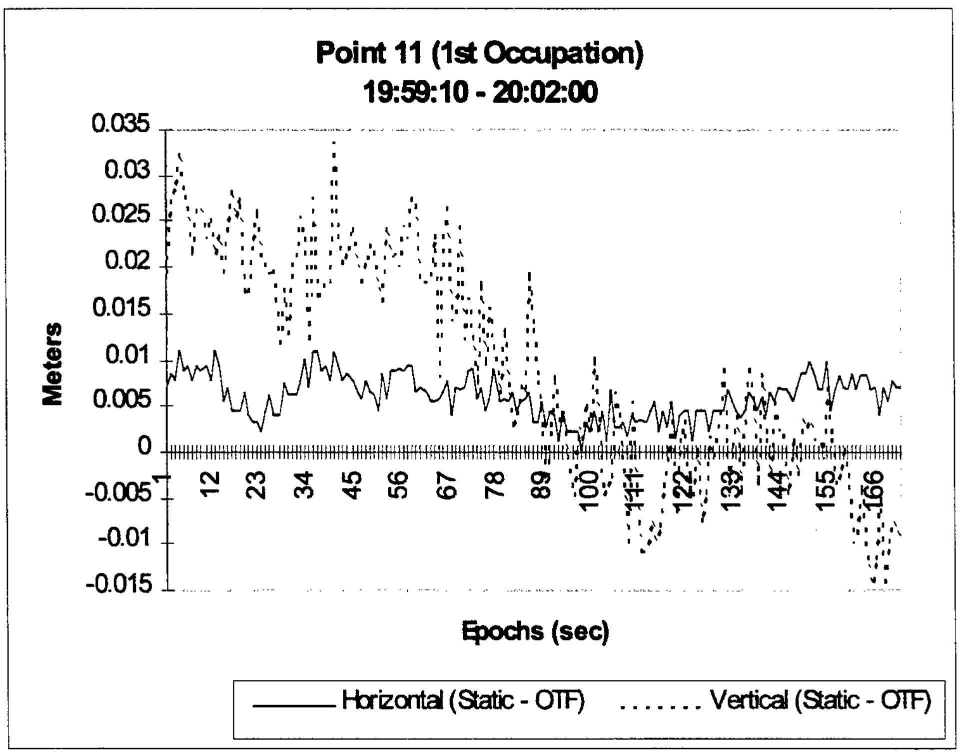
Point 5R (1st Occupation)
20:13:10 - 20:14:30
Meters
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)



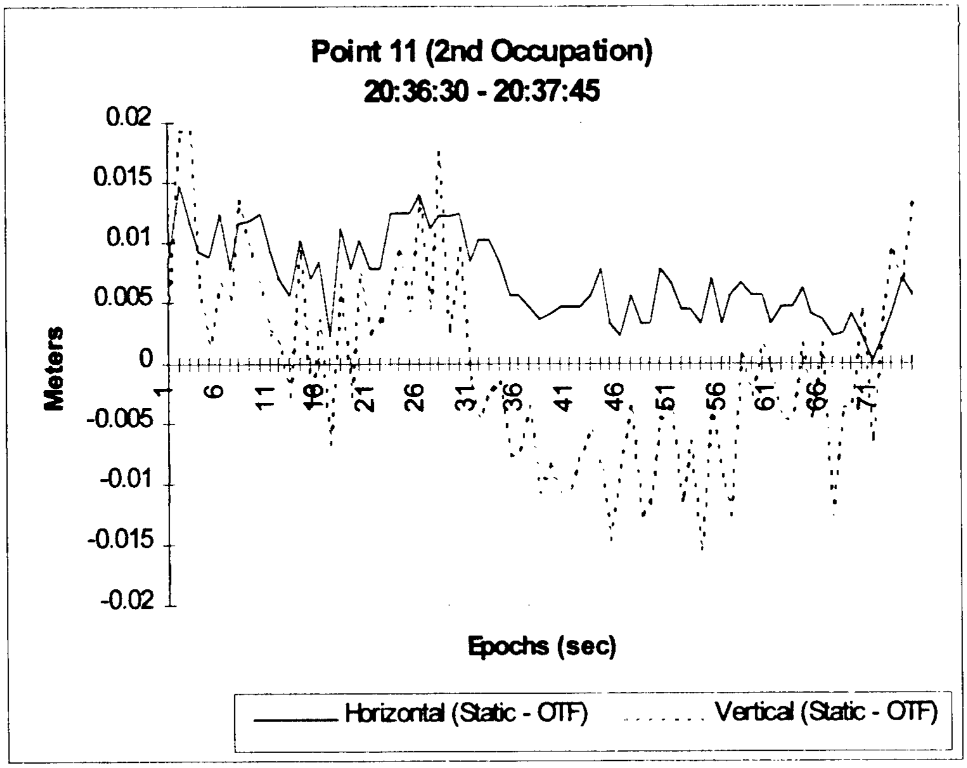
Point 5R (2nd Occupation)
20:50:40 - 20:52:00
Meters
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

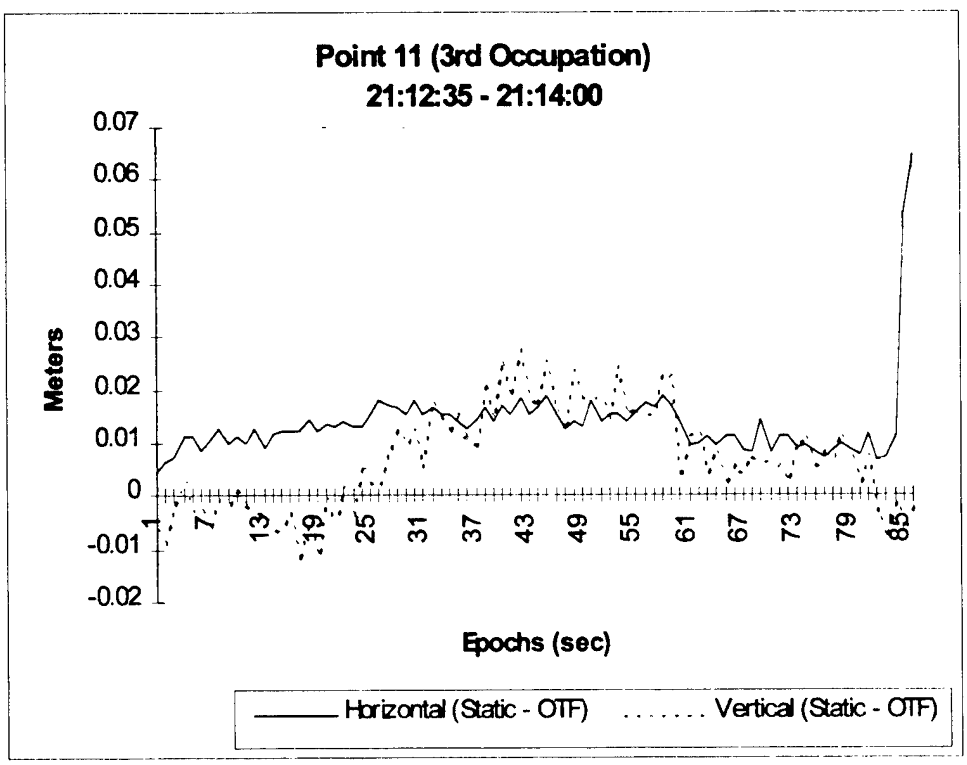


Point 5R (3rd Occupation)
21:25:11 - 21:26:30
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Meters
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)



Point 11 (1st Occupation)
19:59:10 - 20:02:00
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Meters
1
12
23
34
45
56
67
78
89
100
111
122
133
144
155
166
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)


Point 11 (2nd Occupation)
20:36:30 - 20:37:45
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Meters
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

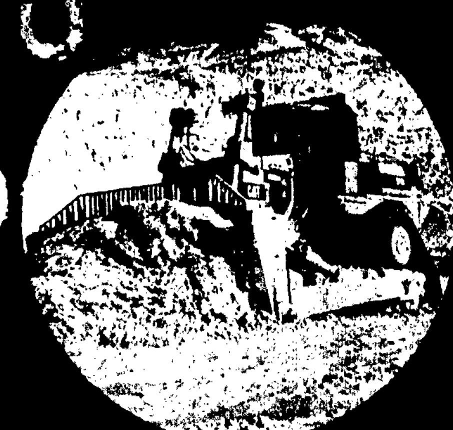

Point 11 (3rd Occupation)
21:12:35 - 21:14:00
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
Meters
1
7
13
19
25
31
37
43
49
55
61
67
73
79
85
Epochs (sec)
Horizontal (Static - OTF)
Vertical (Static - OTF)

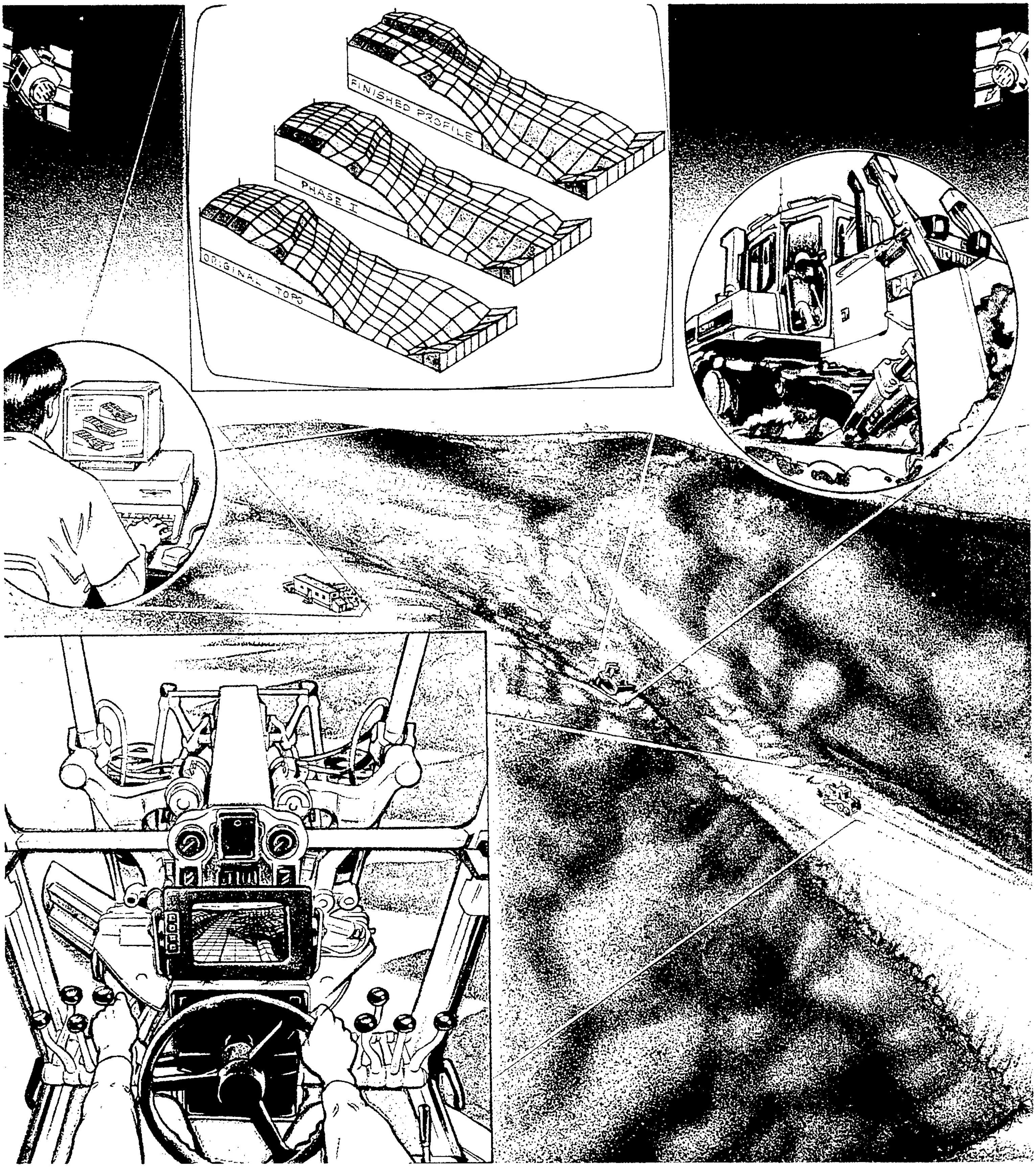
APPENDIX D

CAES Documentation

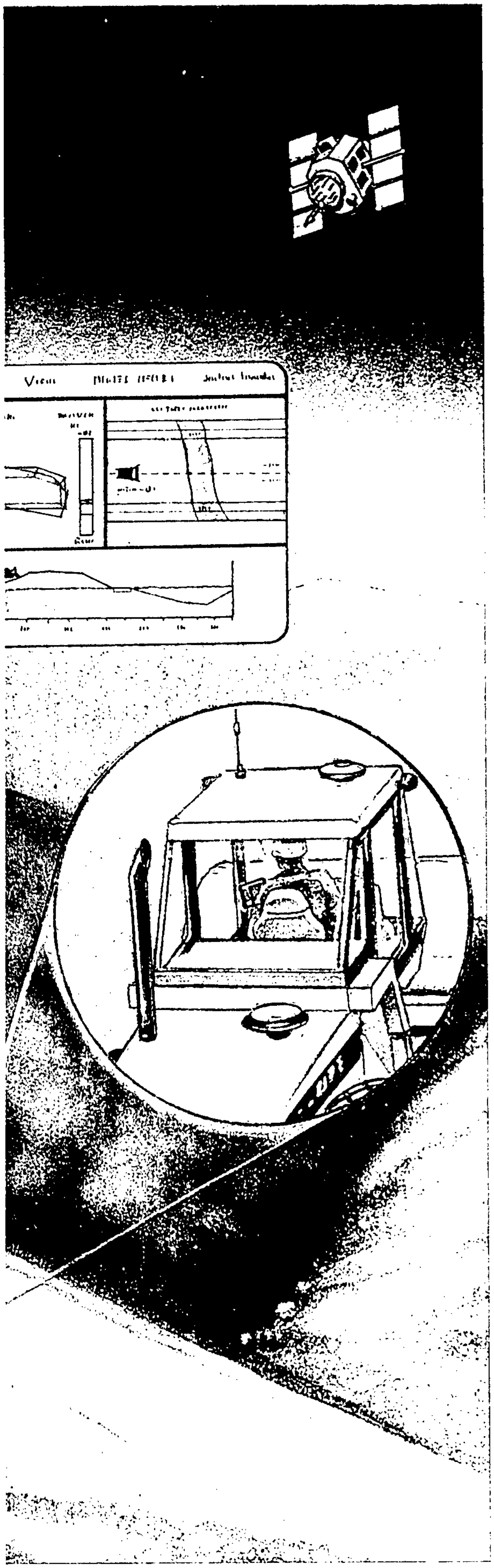
Caterpillar®

Computer Aided Earthmoving Systems



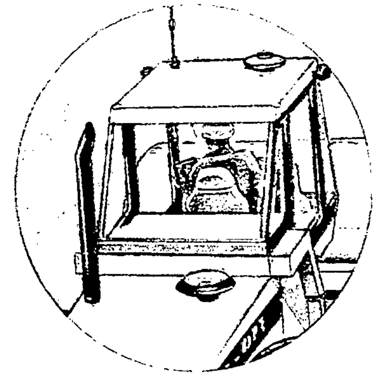


Caterpillar's new Computer Aided Earthmoving System (CAES), allows precise earthmoving using the Global Positioning System and machine-mounted computers. Plans are electronically transferred to machine operators in real time 2-D or 3-D color graphics, improving communication and reducing the possibility of human error



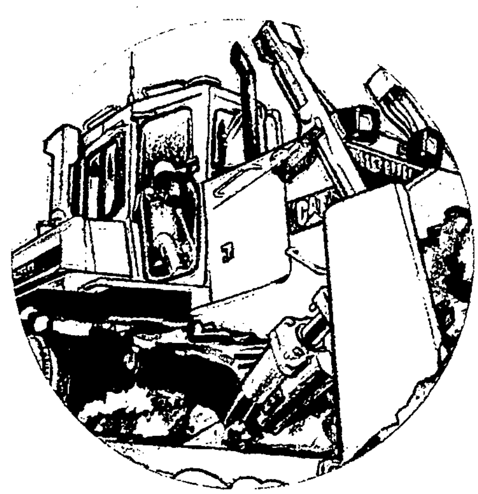
Innovation

Today, earthmoving machine operators receive their information and instructions through an intermittent, manpower intensive, and costly process. The process typically begins with a survey of the site, accompanied by the identification and location of natural and man-made structures. Working with this information, the planning engineer designs the project. These designs are transferred to the field by another survey, with survey stakes located and marked at key locations. Hundreds or even thousands of stakes defining elevations and grades may be required. Furthermore, field foremen and paper plans usually supplement the survey information. As the job progresses, additional surveys may be required to convey information on the next phase, to make changes to the current work, and to document completed work against plan. Not only is this process time-consuming and expensive, it contains numerous opportunities for error.



With a constant flow of real time information to the operator, precise compaction is easier and faster, thanks to CAES. CAES also tracks and updates information for the operator as tasks are completed, increasing job quality and reducing idle time.

The Caterpillar Computer Aided Earthmoving System uses machine-mounted computers in conjunction with high-accuracy Global Positioning System (GPS) receivers, data radios, and displays to provide machine operators and site managers with a variety of real time information regarding the execution of the earthmoving task. Earthmoving plans generated with conventional, commercial software are electronically transferred to the machine-mounted computer and displayed in color graphics to the operator. These plans have included 2-D or 3-D topographic maps, desired grades and slopes, geometric descriptions of ore bodies and a number of desired compactor passes. As additional CAES applications are developed, other information important to the earthmoving process will be displayed. GPS is used to locate the machine. The machine's location and the work plan are simultaneously displayed in real time on the operator's screen. CAES graphics have zoom capability to permit the operator access to broad site plans or detailed localized plans, depending upon the immediate need. As work progresses, CAES measures and records the machine's accomplishments and updates the information for the operator. For example, a grading machine operator has information that tells him where he is located relative to the planned job, what the finished surface at that location is to be, and what the current surface is. The same information that is available to the machine operator is transferred back to the engineering or management office for analysis and documentation.



CAES improves the quantity, quality and frequency of information that flows to and from the office and field. This information is available upon demand from either the field or the office. Relative to the current methods of surveying, staking, paper plans, and extensive field supervision, CAES reduces manpower, reduces mistakes, minimizes material usage, improves documentation, minimizes machine idle time, and improves job quality. Individually and in combination, these reduce the cost of earthmoving and the cost of construction.

Caterpillar has been performing CAES research work dealing with grade and slope information on track-type tractors, mine ore body information on wheel loaders, and compaction information on landfill compactors. In each case, CAES displayed the real time information that the operator needed for executing the earthmoving task, recorded the machine's accomplishments, and communicated information to the site engineer or manager. Experimental field tests have been conducted under terms of confidentiality at customer sites: landfills, mines, and military installations. Highway construction has been simulated at Caterpillar's Peoria Proving Grounds. These field tests have proved the technical feasibility of CAES. More importantly, from the standpoint of supporting the argument that CAES has the potential to bring about an industry-wide revolution in earthmoving, Caterpillar sees CAES applications for most machines in most markets. Furthermore, the company believes CAES can be cost-effective for most of these applications.

The major components and technologies of CAES are the following: software to access the job plan data and extract the information needed by the earthmoving machine operator, an on-machine computer, on-machine software to store and manipulate data, a display screen, GPS to determine the machine's position and to conduct real time survey of the job site as it changes as a result of machine operation, and wireless communications links to connect machines to the office and to each other. These components are the same for all applications and machines. Application specific software creates CAES products for different machine types and for different machine applications. This commonality of basic components has been a key to the rapid development of CAES and will be crucial in CAES commercialization.

By communicating grade and slope information, track-type tractor operators are aware of their location relative to a job, what the current surface condition is and what the finished surface should be. The result is greater productivity and fewer errors.

Global

Earthmoving, moving and shaping the earth, is fundamental to all civil construction works, mining, agriculture, and many military operations. There are nearly a million active earthmoving machines in the U.S., and twice that worldwide. The world

depends on these machines to prepare the earth for transportation, housing, communication, food production, sanitation, defense, and facilities for work and play. Imagine an innovation that cuts across all these applications, permitting these machines to work faster and better, at less cost, and with fewer mistakes. Imagine an innovation that couples the power of these machines to the power of the electronic computer. The Caterpillar Computer Aided Earthmoving System (CAES) is that innovation which could drive sweeping [illegible] in ea[illegible] of the future.

[illegible] and [illegible]ication technologies have revolutionized many industries: retailing, banking, manufacturing, and engineering, to name a few. Many segments of the construction process have already been impacted by these technologies. Engineers and planners use a wide variety of computer aided design tools to produce earthmoving job plans. However, methods for delivering these plans to the job site and to the machines have remained virtually untouched by computer and communications technologies–until now! The innovative research described in this application is the beginning of a revolution in earthmoving.